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AN OMNIDIRECTIONAL PRESSURE GAGE FOR MEASUREMENT OF WEAK BLAST WAVES

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Ballistic Research Report No. 150

AN OMNIDIRECTIONAL PRESSURE GAGE FOR MEASUREMENT OF WEAK BLAST WAVES

Prepared by:
John L. Lankford

ABSTRACT: An aerodynamic sensor has been developed which is applicable to the measurement of the static pressure behind weak blast waves. The sensor is a ventilated sphere suitable for use with various types of electronic sensing units. A method used for prediction of response characteristics, ventilation coefficients, and sizing parameters gave good preliminary results in the range of 3 to 10 psi overpressures. Preliminary test results indicate a considerable increase in omnidirectional capability over previous gage types for this application. The preliminary program was limited to design of an experimental configuration and evaluation of concept feasibility.

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The author wishes to acknowledge the work of Dr. R. E. Wilson and Dr. A. E. Seigel in initial examination of the concept.

The assistance of many others in the Ballistics, Aerodynamics and Explosions Research Departments of NOL is also appreciated. In particular, the help of Mr. J. F. Pittman, Mr. J. E. Berry and Mr. T. O. Anderson of the Air Ground Explosions Division is acknowledged.

The assistance of Mr. Hensel Brown with programming and Mr. Alan Stern with computations, programming and general project work is greatly appreciated.

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Captain, USN
Commander

A. E. Seigel
A. E. SEIGEL
By direction

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LIST OF SYMBOLS

C_p	Pressure coefficient, $\dfrac{P_{local} - P_\infty}{q_\infty}$
$\bar{C}_p$	Average or area weighted pressure coefficient obtained from pressure distribution
P	Static or stream pressure, pounds per square inch
P_2/P_1	Pressure ratio across moving shock front
q	Dynamic pressure, $1/2\ \rho v^2$
$\bar{R}e_d$	Reynolds number based on sphere diameter and free-stream conditions behind shock
T	Absolute temperature, degrees Rankine
V	Free volume inside sphere, cubic inches

Subscripts

$\infty = o$	Free-stream conditions surrounding the gage
i	Internal (inside spherical sensor)

INTRODUCTION

Formidable problems are encountered in the measurement of strong blast waves associated with high overpressures, three-dimensional and unsteady flow effects. Weak blast waves, however, can be satisfactorily studied and simulated using plane wave theory in which low overpressures, one-dimensional quasi-steady flows, and relatively slow response times (1000 to 5000 cps) are characteristic.

Field studies of air blasts have led to the requirement for a simple sensor that is relatively insensitive to the direction from which a weak blast wave approaches. It is also highly desirable in a field measurement gage that a reading of the static pressure behind the wave front be obtained directly (within a few percent error for low overpressures) without recourse to complex or tedious calibration tests, charts, or iterative procedures.

In the past, the measurement of weak blast waves has been accomplished in the most part by two approaches. One type of gage used was the streamlined aerodynamic shape with pressure orifices or electronic pickups located so that the measured pressure was a value close to that of the static stream pressure behind the blast front. Wind tunnel studies were used to locate orifice position for uncorrected gages (satisfactory for weak waves) and to calibrate the error at values equivalent to moderate blast pressures.

The second approach employed Pitot type gages using tuned cavities so that the resultant pressure in the cavity could be calibrated against the static or total pressure behind a weak blast wave.

These gages required critical orientation with the direction of wave travel and/or tedious and complex calibration and manufacture (reference (1)).

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The small (~1MM) spherical piezoelectric gage (reference (2)) has shown attractive omnidirectional characteristics for blast wave measurement. In addition, for weak waves the local surface pressure on a sphere will differ from the static pressure only by an amount roughly equal to the dynamic pressure. Since for the flow behind weak waves this dynamic pressure is small compared to the static pressure, the sphere appeared to offer possibilities as a sensor housing requiring little or no correction for the measurement of static pressure (references (3) and (4)).

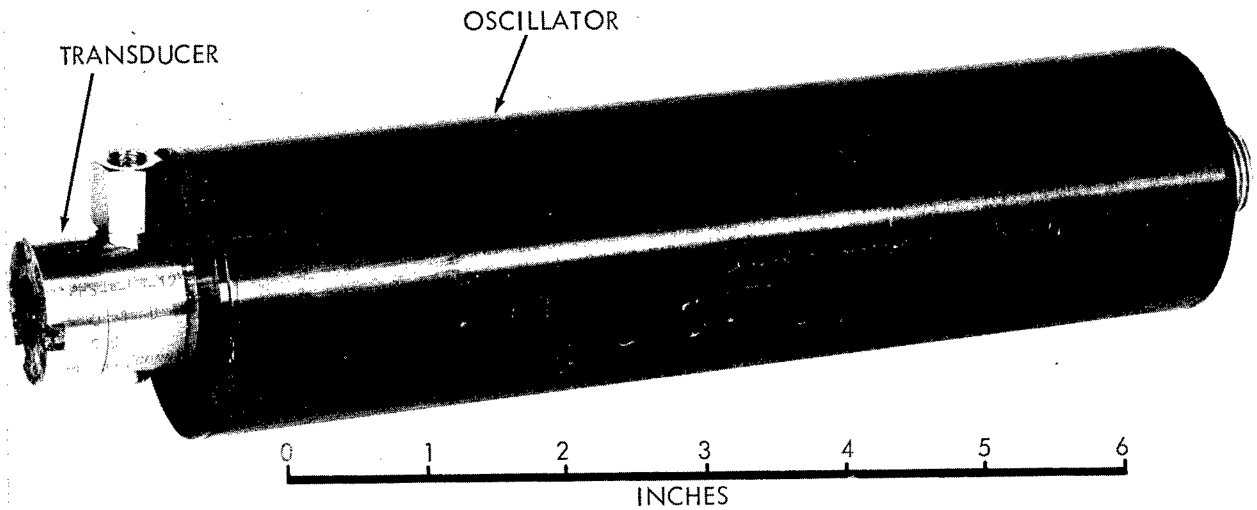


FIG. 1 EARLIER MODEL OF VARIABLE RELUCTANCE GAGE AND OSCILLATOR

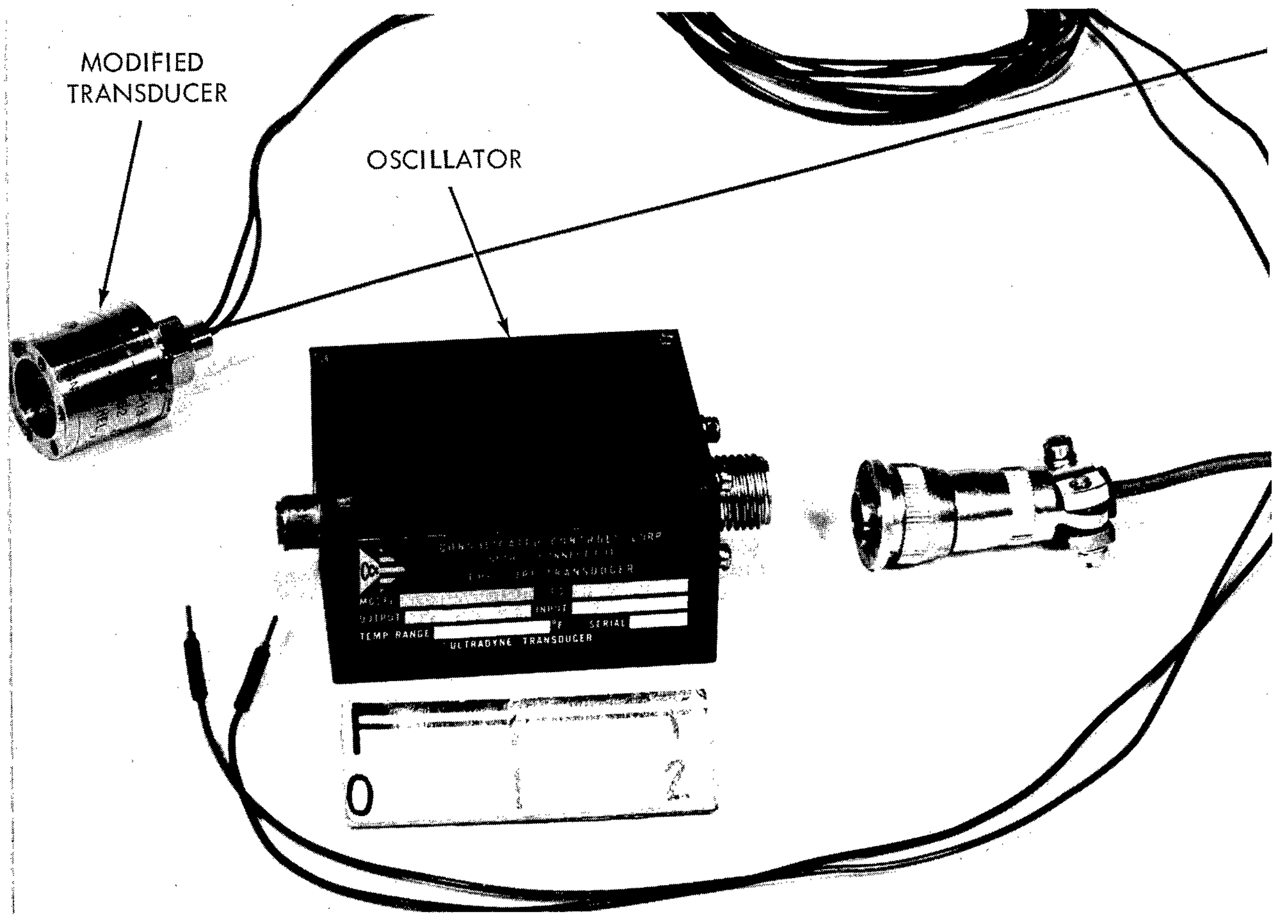


FIG. 2 MODIFIED TRANSDUCER DESIGN FOR OMNIDIRECTIONAL SENSOR

SPECIAL REQUIREMENTS

In addition to requirements for simplicity and omnidirectional characteristics, it was desirable to develop an aerodynamic sensor that could be used with electronic sensing and recording equipment already in use by the Navy in explosions research. One unit presently in use employs a variable reluctance flat diaphragm gage in conjunction with an oscillator to send a frequency modulated signal to a tape recorder in a remote location. This FM system has an overall frequency response to a step pressure pulse of from 1/2 to 1 millisecond. Figure 1 shows the transducer-oscillator unit built by Consolidated Controls Corporation.*

In order to obtain a transducer employing the variable reluctance gage that was compatible with the size limitations (discussed later under Analysis of Sizing Parameters), it was necessary to modify the gage shown in figure 1. The modifications specified by NOL were incorporated into the Consolidated Controls Corporation* gage shown in figure 2.

This design permits encapsulation of the transducer in a sphere of approximately two inches outside diameter and allows for remote location of the oscillator.

Figure 3 illustrates a field application employing the combination of omnidirectional sensor, variable reluctance transducer, FM transmission, and tape recorder. Although this gage concept should eventually be applicable to many systems of measurement, the one illustrated was chosen as a practical one for initial evaluation.

AERODYNAMIC CONSIDERATIONS

Although the sphere has been the object of extensive analytical and experimental study by hydrodynamicists and aerodynamicists for many years, actual measured pressure distributions over ranges of Reynolds number and with various mounting configurations are surprisingly scarce. Results of drag measurements and turbulence investigations are easily found in experimental literature, but pressure distributions are less plentiful (reference (5) and Bibliography).

*The use of company and trade names for instrumentation and equipment in this report does not constitute Government endorsement or criticism of these products.

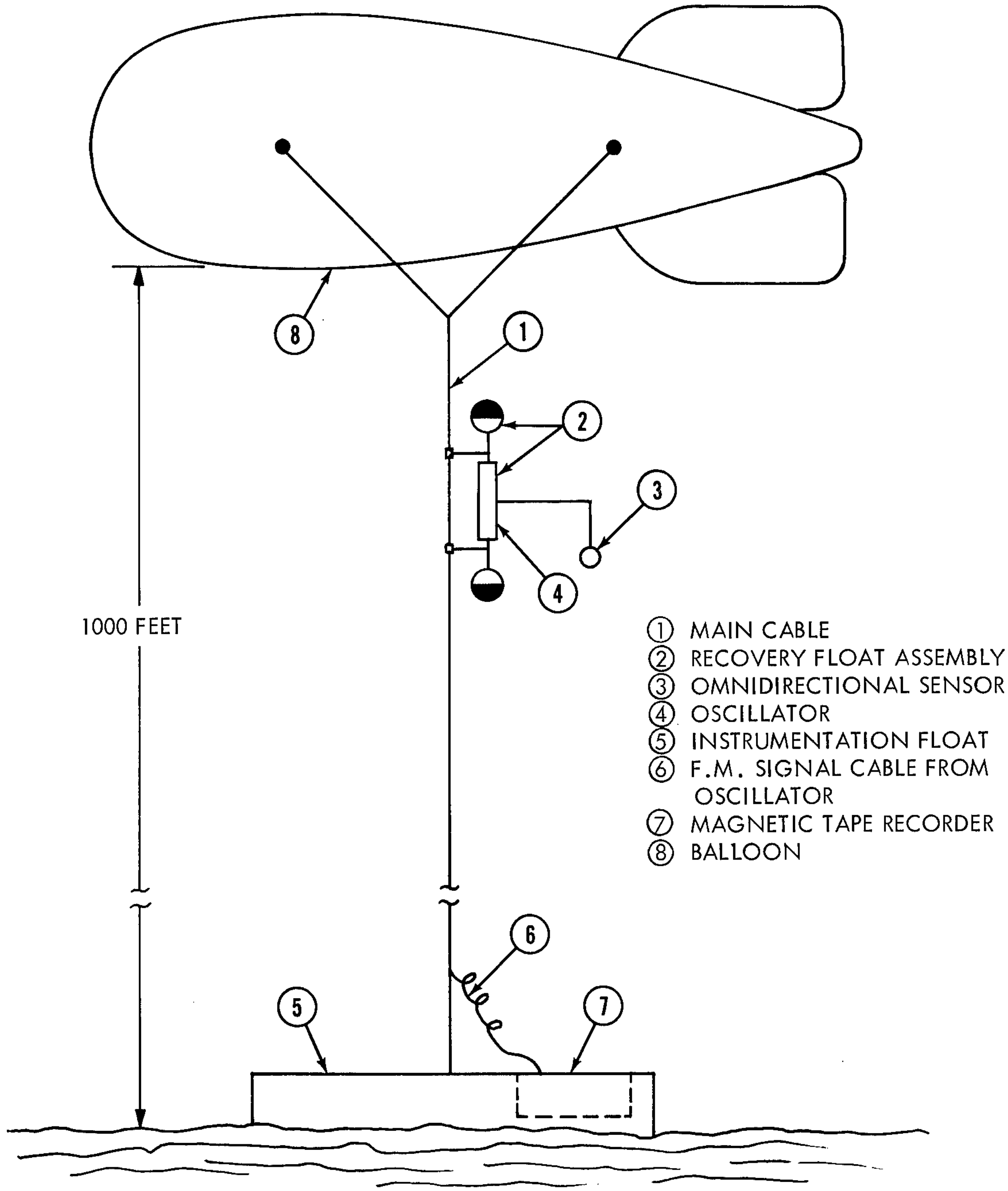


FIG. 3 EXAMPLE OF FIELD APPLICATION FOR OMNIDIRECTIONAL SENSOR

Reynolds number has a strong effect upon the location of the separation line in the flow over a sphere. The effects of subcritical flow (laminar separation), critical flow (transitional separation), and supercritical flow (turbulent separation) on the pressure distribution over a sphere are indicated in figure 4.

In this figure, the local pressure coefficient, Cp is plotted versus the angle measured from the forward stagnation point on a sphere. The effect of this range of profiles on the mean or area weighted surface pressure coefficient $\bar{C}p$, is indicated in figure 5. For the representative profiles selected, a maximum range of mean pressure coefficient from -.3 to -.5 is indicated.

The present sensor application was for blast overpressures (pressures over atmospheric) from 3 psi to 10 psi. Appendix A contains a discussion of the application of simple one-dimensional unsteady flow theory to the use of shock wave parameters for simulation of weak blast wave conditions. The range of conditions for this application is given in figures 6 and 7.

Although the actual conditions after a blast wave change from those indicated by simple one-dimensional theory (references (3) and (4)), the ratio of dynamic pressure to static pressure becomes smaller. Errors based upon the value of q/p static tend to become smaller after passage of the wave.

If the values of $\bar{C}p$ are considered to lie somewhere between the extremes of figure 5 and the effect of sting mounting and ventilation are assumed small or negligible for the first approximation, theoretically the characteristic curve of a spherical sensor should lie in the shaded region of figure 8.

Even with no correction of any kind applied and with an assumed $\bar{C}p$ of -.5, the maximum error at 10 psi overpressure is 12 percent. A crude assumption of a value for $\bar{C}p$ and a theoretical correction for the error due to dynamic pressure should greatly reduce this error. Calibration of an actual gage through the range of operating conditions should reduce the final error to a small value.

The very favorable characteristics indicated for the uncalibrated sensor, based upon this simple analysis, are a strong argument for a rapid preliminary evaluation of the basic concept to confirm feasibility and establish design procedures. This was the objective of the preliminary work reported in this paper.

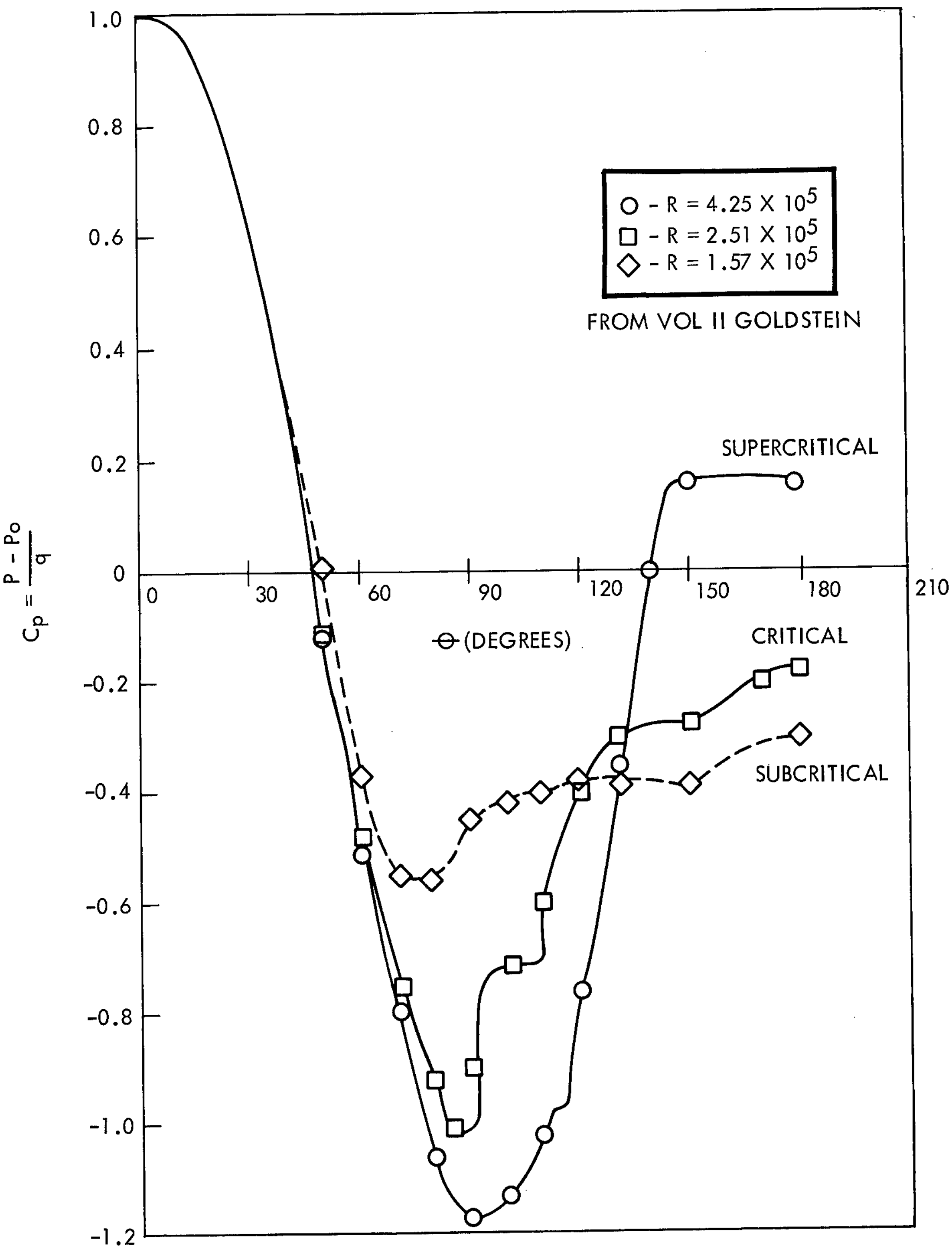


FIG. 4 TYPICAL PRESSURE DISTRIBUTIONS USED FOR EVALUATION OF $\bar{C}_p$.

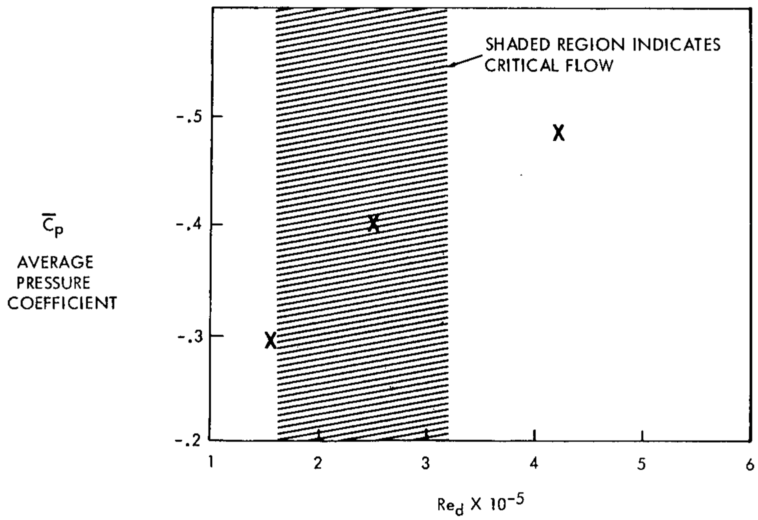
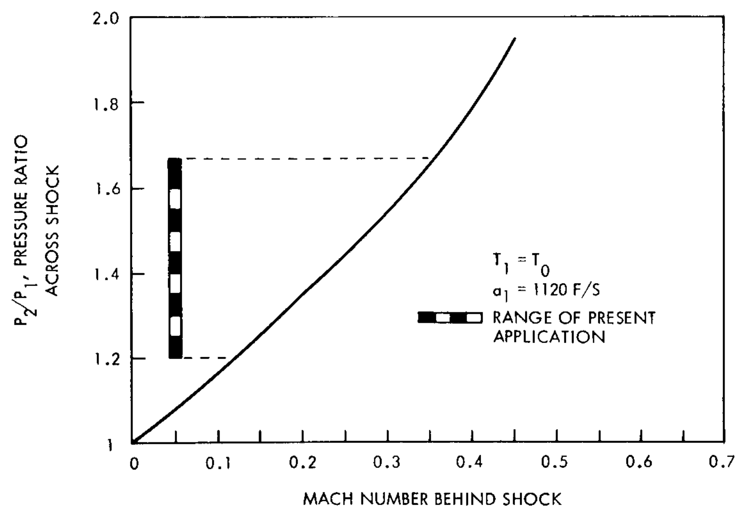
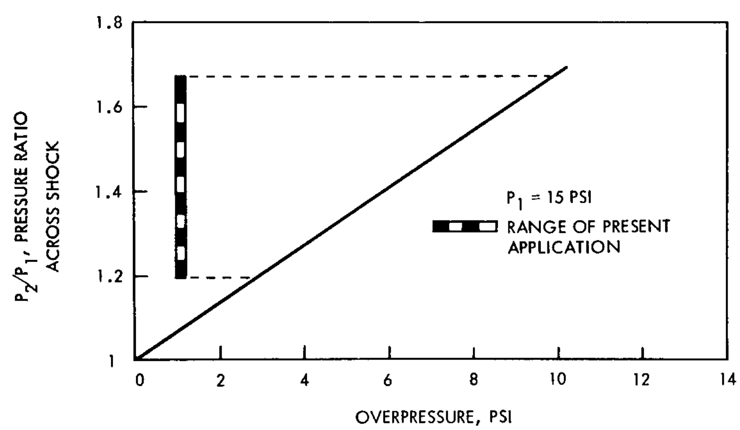


FIG. 5 AVERAGE PRESSURE COEFFICIENTS FOR SELECTED PRESSURE DISTRIBUTIONS



(A)



(B)

FIG. 6 SENSOR OPERATING RANGE RELATED TO ONE DIMENSIONAL SHOCK TUBE PARAMETERS.

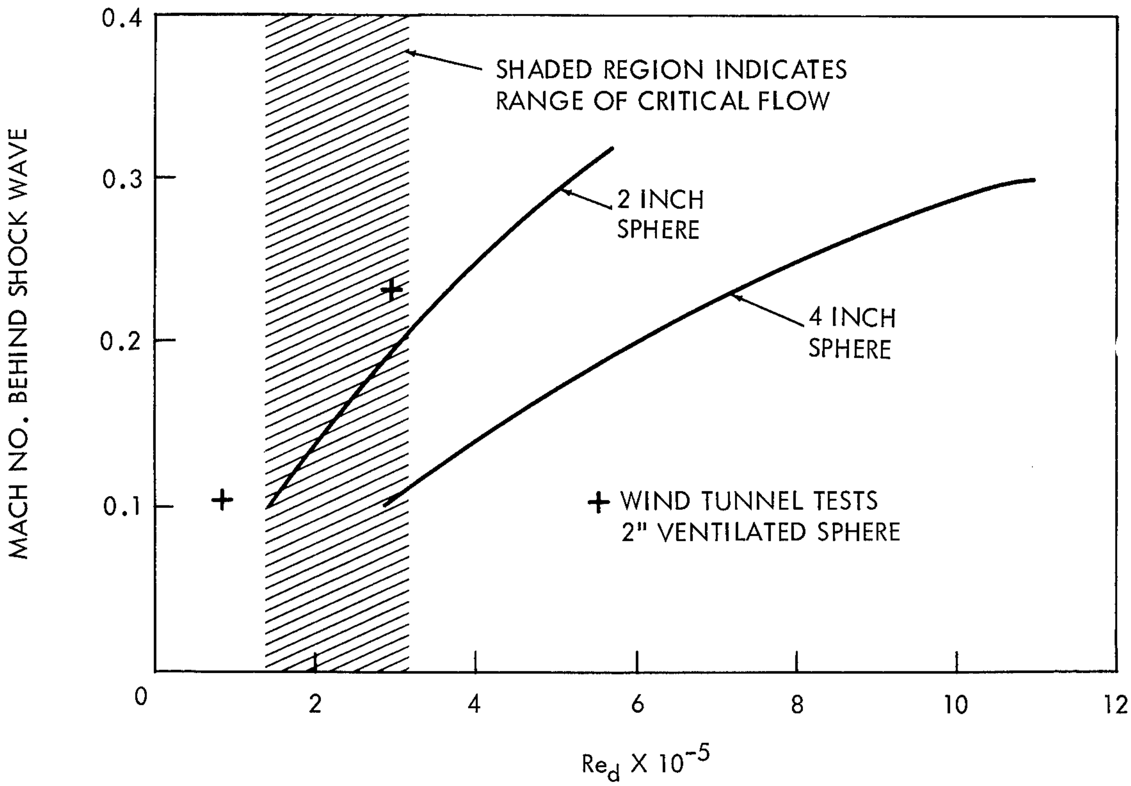


FIG.7 REPRESENTATIVE VALUES OF REYNOLDS NUMBER FOR TYPICAL SENSOR SIZES AND OPERATING CONDITIONS

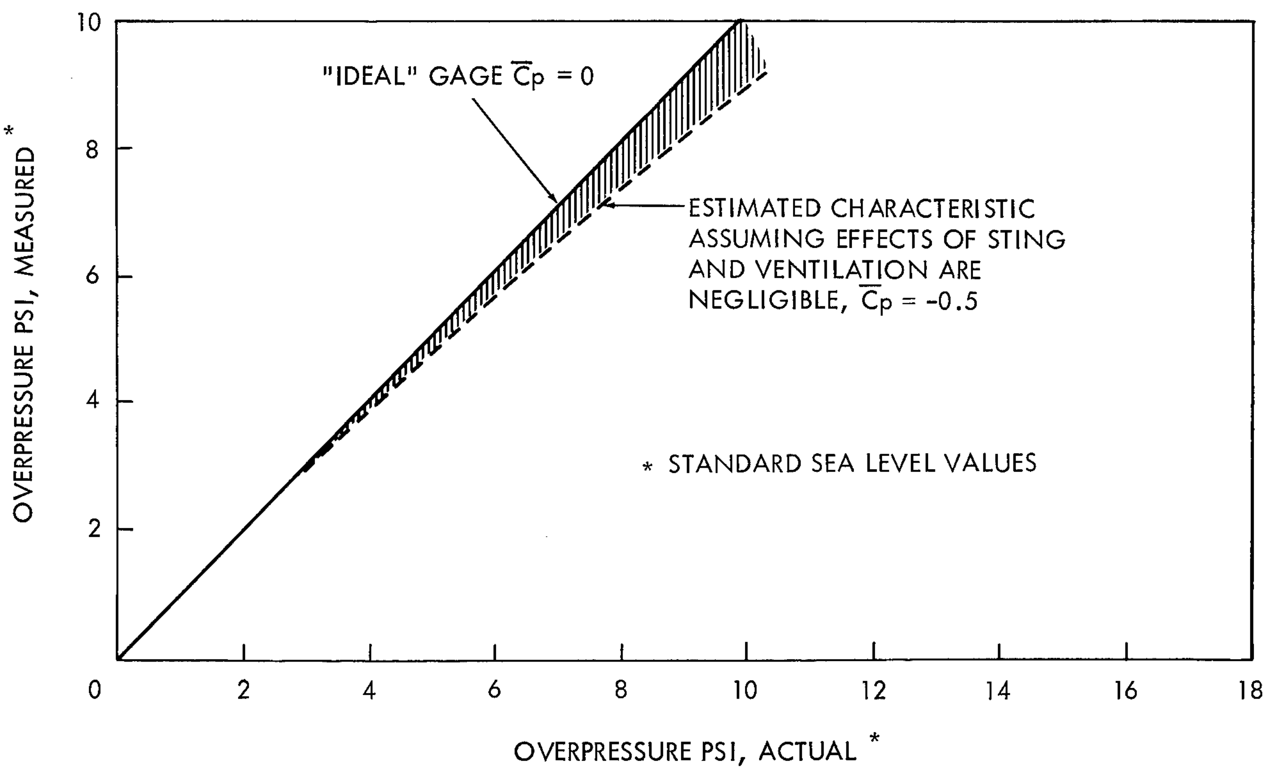


FIG.8 ESTIMATED CHARACTERISTICS OF SPHERICAL SENSOR

MAJOR PROBLEM AREAS

Although preliminary evaluation of the concept indicated that an uncalibrated sensor should give good approximate indications of static pressure behind weak blast waves, several important questions remain to be answered in evaluation of the concept.

1. What methods will provide acceptable information for sizing and ventilation characteristics?

2. Will the flow about a ventilated sphere produce similar pressure profiles to those assumed in the simple analysis?

3. Will an equilibrium internal pressure be reached inside the sphere which will result in characteristics similar to those used in the preliminary analysis?

4. Will a ventilated, mounted sensor exhibit satisfactory omnidirectional characteristics?

5. Can a simple method of estimating response characteristics be developed?

Within the scope of this study, an affirmative answer to the above questions would indicate the general feasibility of the concept. Detailed analytical or experimental procedures or complex calibration methods were beyond the scope of this program. A rough estimation of size and response characteristics was made, therefore, based upon simplified assumptions, and a configuration was designed for preliminary evaluation in a conical shocktube.

ANALYSIS OF SIZING PARAMETERS

Response considerations involving the passage time of the shock over the sensor indicate that a sensor size of less than an inch or two is desirable. In this case, practical considerations of the electronic sensing units that must be encapsulated dictated that the outer diameter of the sphere be no smaller than two inches. Therefore, for preliminary

analysis sphere diameters from two to four inches were considered. Consideration of a 2-inch sphere impulsively started from rest (reference (6)) indicated that flow would be established in the order of 1/10 of a millisecond, approximately the time required for a weak wave to traverse the surface of a 2-inch sphere.

A 2-inch diameter sphere with a thin wall could encapsulate the electronic sensing element and leave a maximum internal volume of approximately 3 cubic inches. Preliminary estimates indicated this volume to be of the correct order of magnitude for the general response requirements. A machine program was set up involving a numerical solution for the time required to approach equilibrium internal pressure with various combinations of internal volume and ventilation area for a 2-inch sphere. This method is described in Appendix B, and the results of a typical preliminary computation are presented in figures 9 and 10.

The initial application for this sensor was for use with an undamped, flat diaphragm, variable reluctance type pressure transducer, and the response time of the system incorporating this transducer was approximately one millisecond.

Since exciting the natural frequency of such diaphragm gages is frequently a serious problem in their application, it was considered advisable to utilize most of the one millisecond to fill the cavity. This approach would result in an optimum slope of the pressure versus time curve and would avoid "ringing" the gage with too rapid a pressure rise.

As indicated by the results presented in figures 9 and 10, the optimum sizing combination, based upon consideration of all major requirements, appeared to be a 2-inch outside diameter sphere with an internal cavity volume of 3 cubic inches and a ventilation coefficient of 5 percent (percent of surface area ventilated for air flow).

Theoretically, the response characteristics can be improved (shortened) by decreasing cavity volume and increasing ventilation area. This may prove harmful beyond a certain point, however, since in addition to "ringing" diaphragm gages this may cause secondary internal flows and disturb the external flow patterns.

In order to accommodate a variety of electronic sensing gages and to fulfill the requirements set forth by the assumptions of the analysis, it is important that the interior

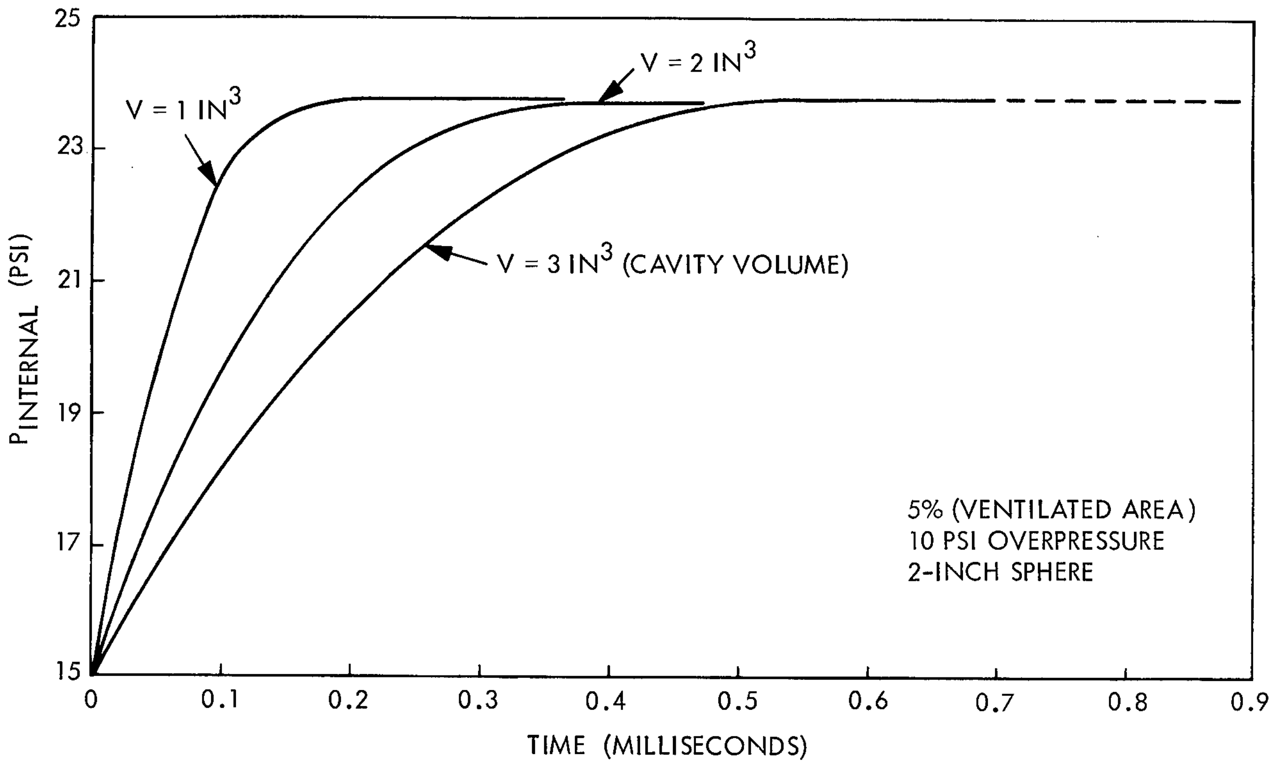


FIG. 9 COMPARISON OF PERFORMANCE WITH DIFFERENT CAVITY VOLUMES FOR A GIVEN VENTILATION FACTOR

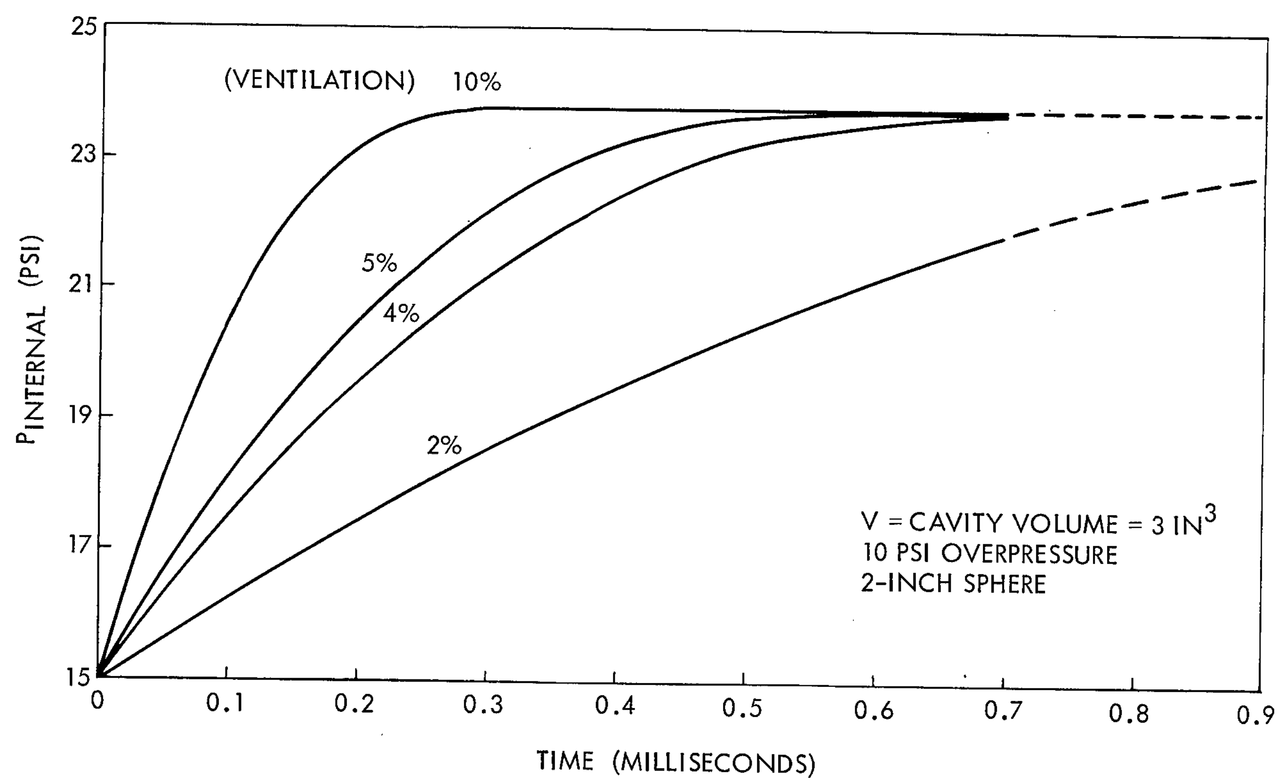


FIG. 10 COMPARISON OF PERFORMANCE WITH DIFFERENT VENTILATION AREAS FOR A GIVEN CAVITY VOLUME

of the sensor act as a plenum chamber. In order to insure this, it is necessary that the ratio of ventilation hole diameter to sphere cavity diameter be very small. Extremely small holes will make fabrication difficult, however, and some reasonable compromise is necessary.

FABRICATION OF A VENTILATED SPHERE

The results shown in figures 9 and 10 are based upon the assumption of certain values of ventilation coefficient and upon the assumption that the flow through the ventilation "area" obeys the laws of flow through small orifices (Appendix B).

By using the proper flow characteristics for some other type of ventilation flow, however, other solutions could be made. For the preliminary configuration used in this program it was most feasible to machine a sphere and perforate it with a large number of uniformly distributed, circular, drilled holes.

The use of porous metal or sintered wire mesh metal products might be more satisfactory for production gages. Some of these materials are available in wide ranges of porosity, and air flow characteristics and can be fabricated into reasonably strong, thin-walled spherical shapes.

Exact design computations should be made for these materials in order to properly apply them; however, figure 11 roughly compares the general air flow characteristics of three commercial grades of sintered wire mesh with the air flow characteristics of the optimum sphere for this application. It appears feasible to consider such materials for the fabrication of production sensors.

Based upon the results of the sizing analysis modified slightly by practical considerations of fabrication and mounting, the ventilated spherical sensor shown in figure 12 was constructed for preliminary evaluation.

The configuration shown is a 2-inch outside diameter sphere ventilated approximately uniformly (not an exact mathematical distribution) with 258 radially directed holes of .055-inch diameter except for the area taken up by the sting mount and support.

The sphere is constructed of brass and is plated inside and out with nickel. A wall thickness of 1/10 inch (thicker than desired) and a threaded joint were necessary in the preliminary model. The model with an LC-70 transducer and a

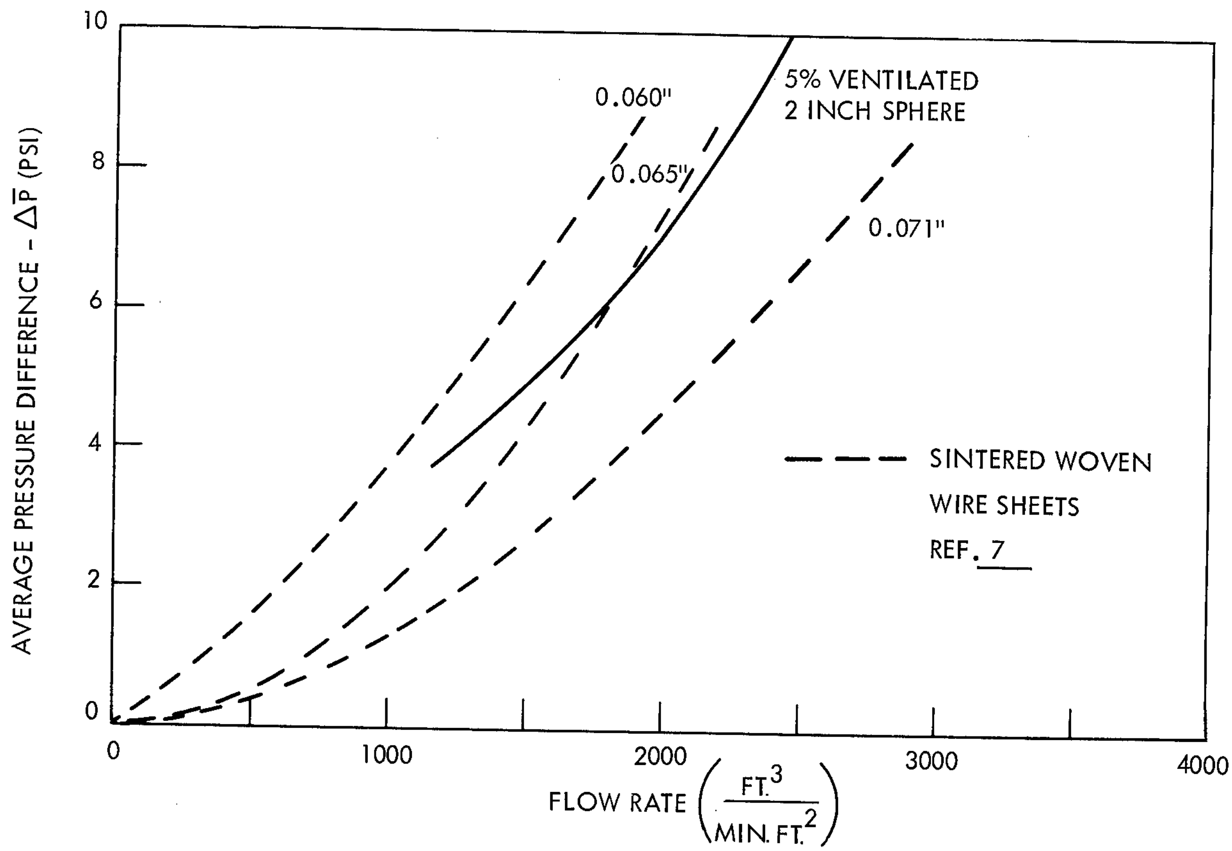


FIG. 11 COMPARISON OF AIR FLOW CHARACTERISTICS OF VENTILATED SPHERE AND COMMERCIAL POROUS SHEETS

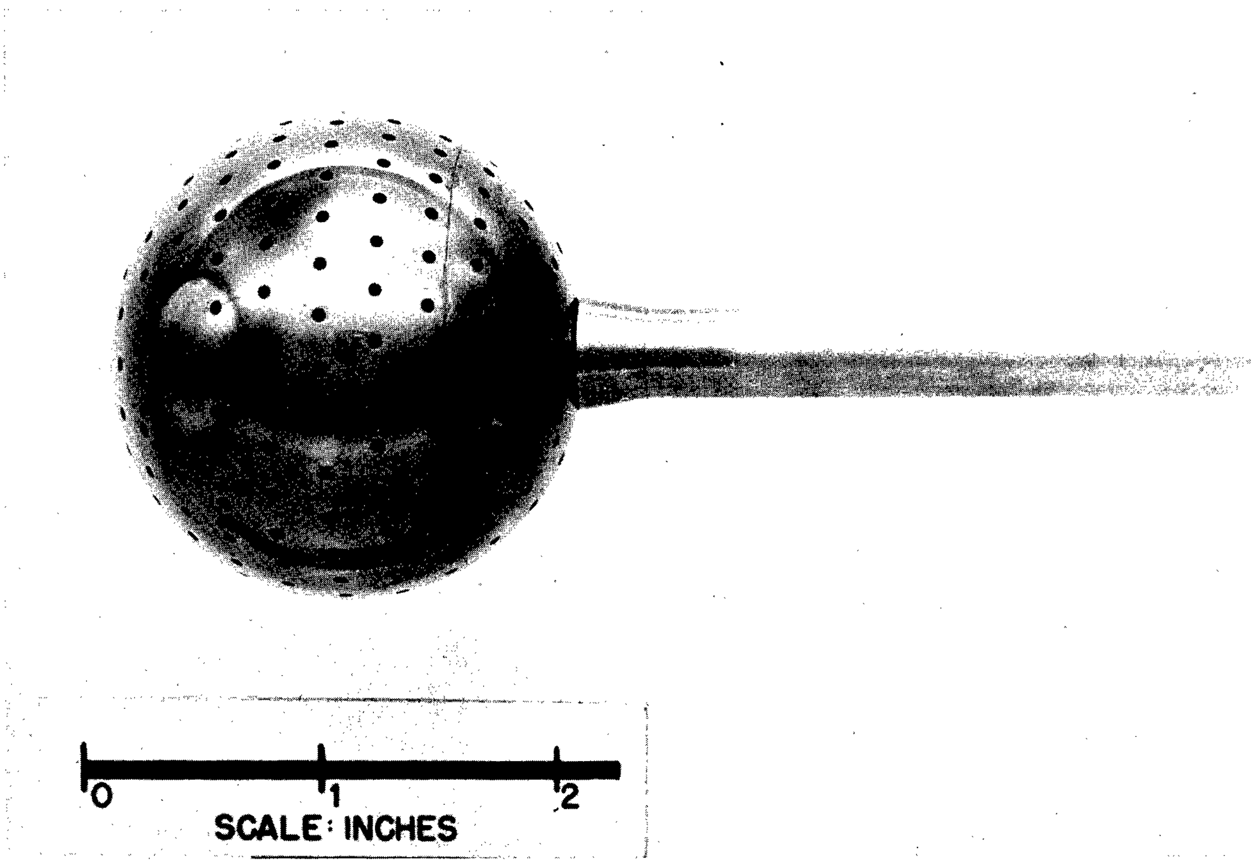


FIG. 12a PRELIMINARY CONFIGURATION OF OMNIDIRECTIONAL BLAST GAGE

NOTES:

1. 125 EXCEPT AS NOTED
2. NICKEL PLATE MIN. .0003 TO .0005 THICK ALL OVER

NO.	B.C. DIA "X"	NO. OF HOLES	SIZE
1	0	1	NO. 54 (.0550) DRILL
2	.445	6	
3	.868	13	
4	1.247	18	
5	1.564	24	
6	1.802	27	
7	1.950	29	
8	2.000	29	
9	1.950	29	
10	1.802	27	
11	1.564	24	
12	1.247	18	
13	.868	13	

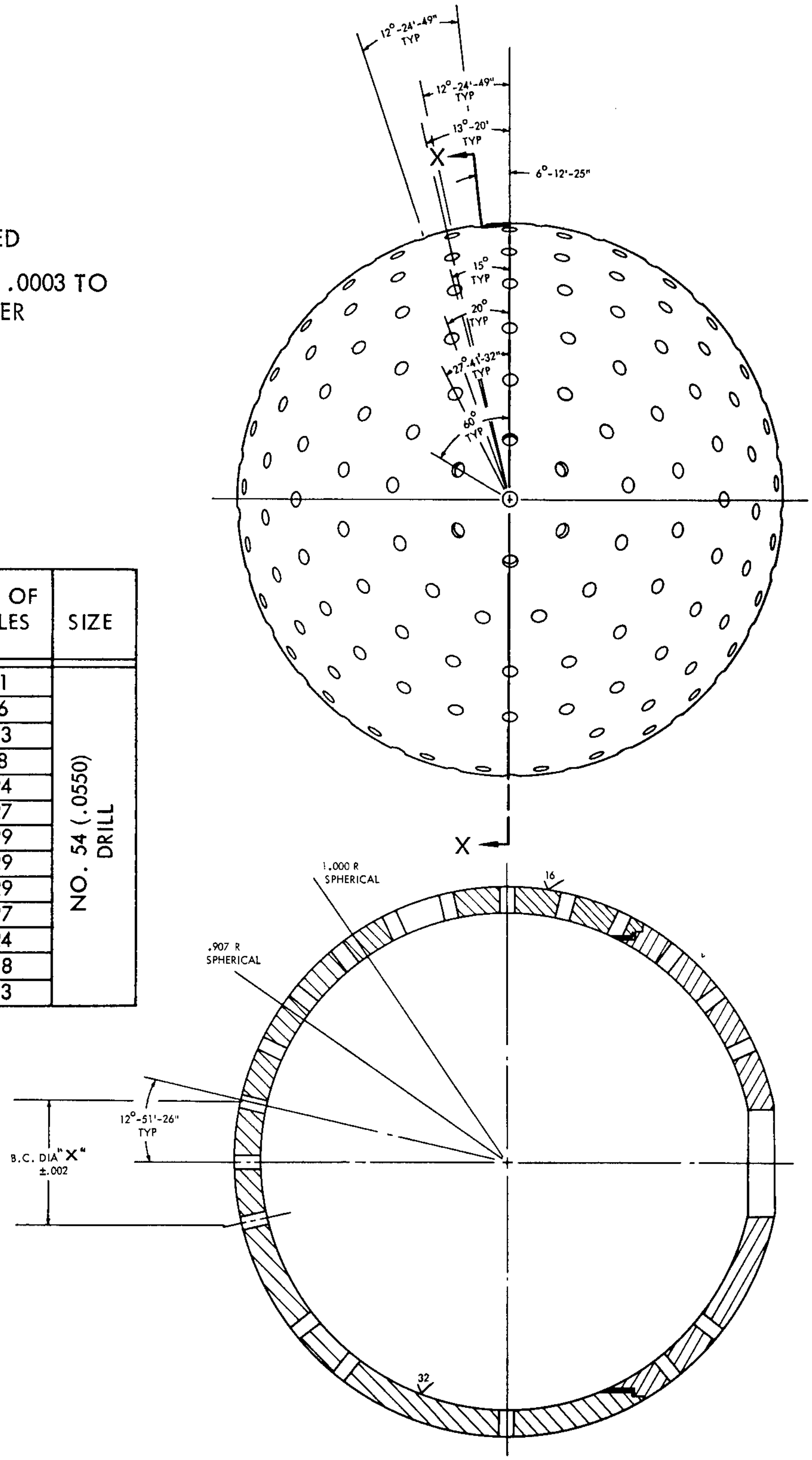


FIG. 12b PRELIMINARY CONFIGURATION OF VENTILATED SPHERE (SPECIFICATIONS)

teflon mount, as used in preliminary tests, had a ventilation of 4.5 percent and a free internal volume of 2.70 cubic inches. When Consolidated Controls Corporation variable reluctance transducer was used the free internal volume was reduced to approximately 2.45 cubic inches.

EXPERIMENTAL INVESTIGATIONS AND EVALUATION TESTS

It was not the objective of the present program to thoroughly explore the characteristics of instrumentation employing a ventilated sphere as an aerodynamic sensor. In order to accomplish such an objective extensive tests and calibrations of many configurations in wind tunnels, shock-tubes and in the field will be necessary.

For precise quantitative evaluation and calibration, large wind tunnels (capable of operation through a wide range of pressures) and large well-instrumented shocktubes are recommended (see Appendix A). The time and expense involved in such an evaluation were beyond the scope of this program. In order to answer the basic questions discussed in the section on Major Problem Areas and to provide a rapid semi-quantitative evaluation of the concept and the preliminary configuration, a short series of wind tunnel and conical shocktube tests were conceived and carried out.

WIND TUNNEL TESTS

A brass mock-up of the modified transducer shown in figure 2 was constructed and fitted with two pressure tubes which could be connected to a sensitive manometer. The large subsonic wind tunnel of the University of Maryland was utilized to run pressure tests on the actual ventilated spherical sensor containing the simulated variable reluctance gage. A photograph of the test setup is shown in figure 13. The support system could be rotated 360 degrees around the center of the sphere to evaluate omnidirectional characteristics. Comparison of the pressures measured by the orifices in the face of the dummy gage with the tunnel static pressure could be utilized in conjunction with tunnel dynamic pressure to evaluate the pressure coefficient for the sensor configuration at any chosen angle of attack.

The value of these simple tests was limited by several factors. The tunnel test section could be operated only at atmospheric static pressure. The Reynolds numbers and over-pressures at which the sensor was being tested were, therefore,

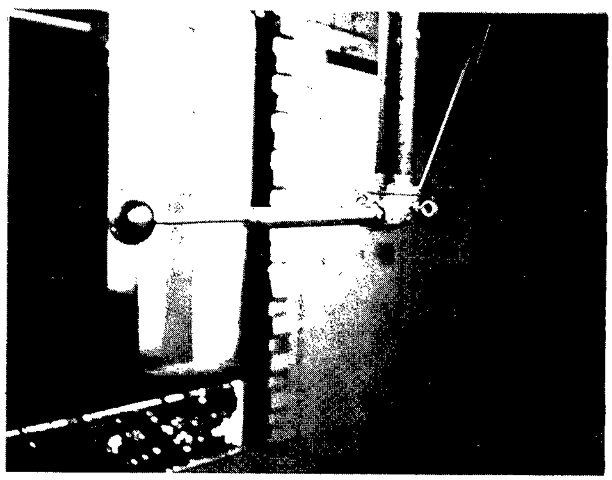


FIG. 13 VENTILATED, 2 INCH, SPHERICAL SENSOR INSTALLED FOR WIND TUNNEL TESTS

not representative of the actual field conditions for which the gage was designed. The entire range of conditions tested, in fact, was in the critical and subcritical range of Reynolds numbers for a solid sphere as indicated in figures 5, 6 and 7.

The results also would indicate only steady state values of pressure, and dynamic response characteristics would not be indicated.

The tests were valuable, however, as a rough indication of omnidirectional characteristics and to indicate whether or not pressure coefficient and flows with the ventilated sphere correlated even approximately with the assumptions of the analysis.

The actual transducers to be used with the spherical sensor indicate a pressure which is representative of a mean or average of the local pressures distributed over the diaphragm or gage face. Local effects such as persistence of jets from the ventilation holes oriented along the flow axis would be averaged out and cause only small or negligible error. With the tunnel configuration, however, since pressure was measured by only two very small orifices at specific locations, unrealistic values could be obtained when the orifices were oriented exactly with the stagnation or center line stream tube. To eliminate errors from this source, loosely compressed steel wool was placed inside the sphere housing between the dummy gage face and the front of the sphere. This acted as a diffuser or mixing zone and eliminated the effect of local jets on the pressure orifices.

It is not expected that this effect is of significance for an actual transducer. In the event that small gages or small internal volumes are used in a design, however, baffles, wire mesh or diffusion materials are recommended to prevent or minimize such effects. Another provision which would reduce this effect would be to decrease the hole diameter of the ventilation holes. The results with and without diffusion material are shown for typical runs in figure 14.

Typical results of the wind tunnel evaluation are presented in figure 15. Although the pressure coefficients at low angles of attack are somewhat smaller (closer to zero) than might be expected based upon unventilated sphere pressure distributions and theory, the values shown indicate that basic flow characteristics with ventilation must be close to those assumed in the analysis of this concept.

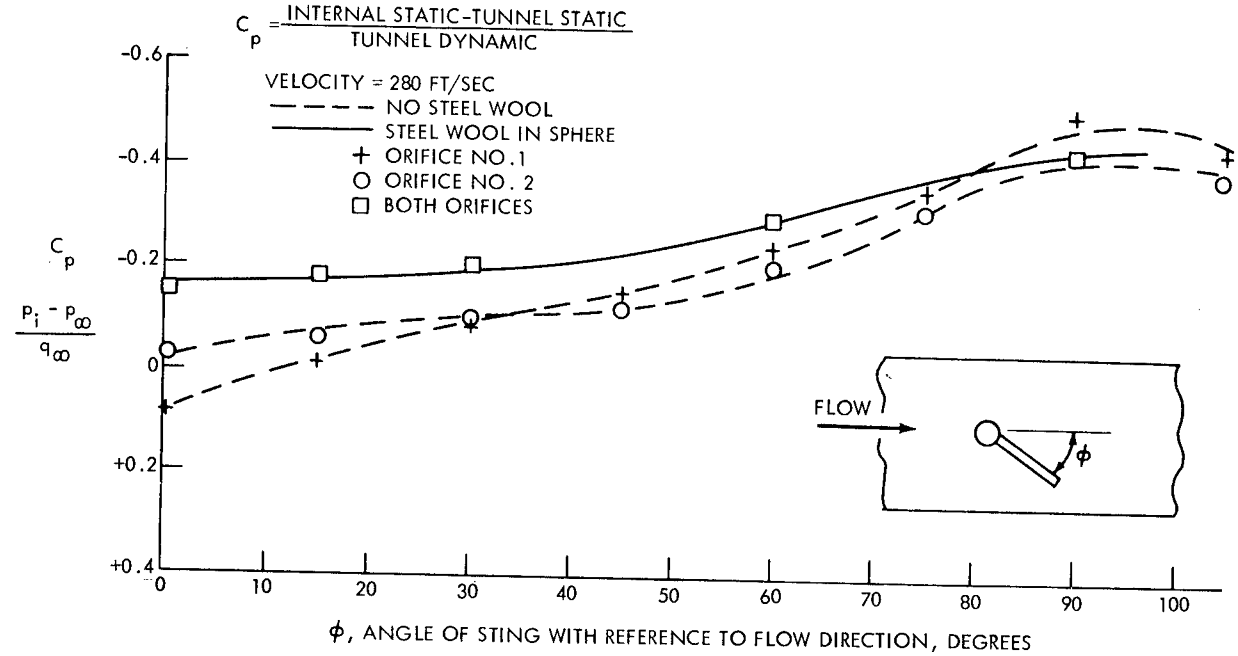


FIG. 14 RESULTS OF WIND TUNNEL TESTS, 280 FT/SEC, $R_{e_d} \sim 2.8 \times 10^5$

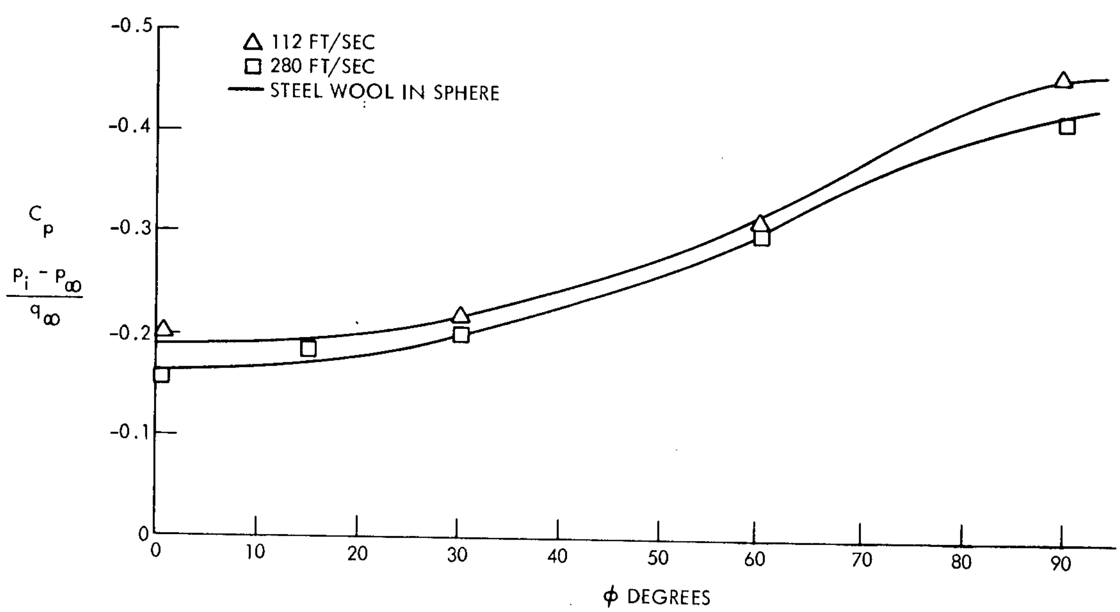


FIG. 15 TYPICAL RESULTS FROM WIND TUNNEL TESTS
(REYNOLDS NUMBERS IN CRITICAL REGIME FOR A SOLID SPHERE)

The differences shown and the exact nature of the angle of attack effects are probably noticeably affected by the variable and transient nature of flow phenomena in this critical regime of flow.

Since this present sensor was designed to operate primarily in regions of higher Reynolds number and overpressure, the quantitative results of the wind tunnel tests should be given less weight than results of dynamic tests under representative conditions.

In general the wind tunnel results confirm the feasibility of the concept. The results indicate that even in the critical flow regime, which may be encountered at low values of overpressure, an uncalibrated gage should give good results within a one or two percent error for angles up to ±90 degrees.

Referring back to figure 8 it can be seen that all the differences shown in figures 14 and 15 would fall within the thickness of a single line at these very low values of dynamic pressure.

A similar evaluation for higher overpressures and Reynolds numbers could be obtained from investigations in a large variable pressure facility (Appendix A).

The expense and time involved were not justified in a preliminary evaluation, however, and it was decided to complete preliminary evaluation of a ventilated configuration as described in the next section.

CONICAL SHOCKTUBE TESTS

Analysis and preliminary wind tunnel results had indicated that an unventilated sphere should exhibit good omnidirectional characteristics even when sting mounted if measurement of static pressure at low Mach numbers was its primary purpose.

Results of numerical solutions based upon simplifying assumptions (Appendix B) had also indicated that reasonable transient response could be expected with practical configurations. A modified electronic gage had been designed which was compatible with field measuring techniques for weak blast waves and which could be integrated with the sensor configurations constructed.

It now remained to determine whether conditions with a ventilated gage would approximate those predicted. Two possible

deviations from theory seemed quite probable. First, the ventilated gage could, because of the effect of ventilation on the flow field, exhibit grossly different mean pressure coefficients than those used for the design analysis. Wind tunnel results in the critical regime were encouraging but actual overpressures and flow conditions had not yet been simulated. Second, the response characteristics could be different from those indicated by such an approximate analysis. If the first deviation were present to a large extent, the basic concept would be of little practical value. If the second occurred, long months of "cut and try" effort might be necessary to arrive at the proper values of design parameters for a given application.

In order to arrive at an early conclusion on the basic unknowns, it was required that a rapid method of overall evaluations be set up under conditions of transient response. Testing the actual aerodynamic configuration with a representative pulse shape appeared to be the only proper course of action.

The conical shocktube (references (8) and (9)) was employed as indicated in figure 16.

Because of the complexity and response limitations of the variable reluctance type electronic sensor and its recording system, it was more feasible to use piezoelectric gages for preliminary studies in the conical shocktube facility. Utilization of a standard and well-known piezoelectric sensor inside the aerodynamic housing in conjunction with similar gages in the tube wall would permit direct comparison of recorded traces for evaluation of response time, pulse magnitude, and pulse shape.

LC-70* gages supplied as stock items by Atlantic Research Corporation were selected. Gages were calibrated in a static test rig manufactured by the gage company and also in a test apparatus developed at NOL for dynamic calibration of pressure transducers (reference (10)). A sample of the calibration results for a typical transducer in both types of equipment is given below.

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*The use of company and trade names for instrumentation and equipment in this report does not constitute Government endorsement or criticism of these products.

TABLE I

BALLISTICS DEPARTMENT
CALIBRATION LC-70 GAGE #190

APPARATUS OF NOLTR 63-143 29 JAN 1965

Pressure PSI	Charge μμ Coulombs
5	535
10	1050
15	1590

Average sensitivity 106 μμC/psi

EXPLOSIONS RESEARCH DEPARTMENT
CALIBRATION LC-70 GAGE #190

ARC CALIBRATION TEST RIG JAN 1965

Range PSI 5 to 14.7

Average sensitivity 106.4 μμC/psi

Figure 17 shows some of the gage components used in preliminary tests. The straight sting, simulated mount, and clamp ring are shown with an LC-70 piezoelectric gage and connector. The simulated mount represents the dimensions and shape of the variable reluctance gage. The preliminary sensor configuration was fabricated with a thicker wall than was originally expected. This was necessary to provide thickness for the threaded portion of the sphere which could be disassembled for changing transducers. The increased thickness reduced internal volume, however, and a smaller mount was designed for the LC-70 gages. This mount was a teflon cylinder threaded to fit the LC-70 gage. Teflon spacers were made so that the LC-70 transducer would have no direct metal contact with the sting or sensor and mechanical noise and vibration would not be transmitted to the transducer.

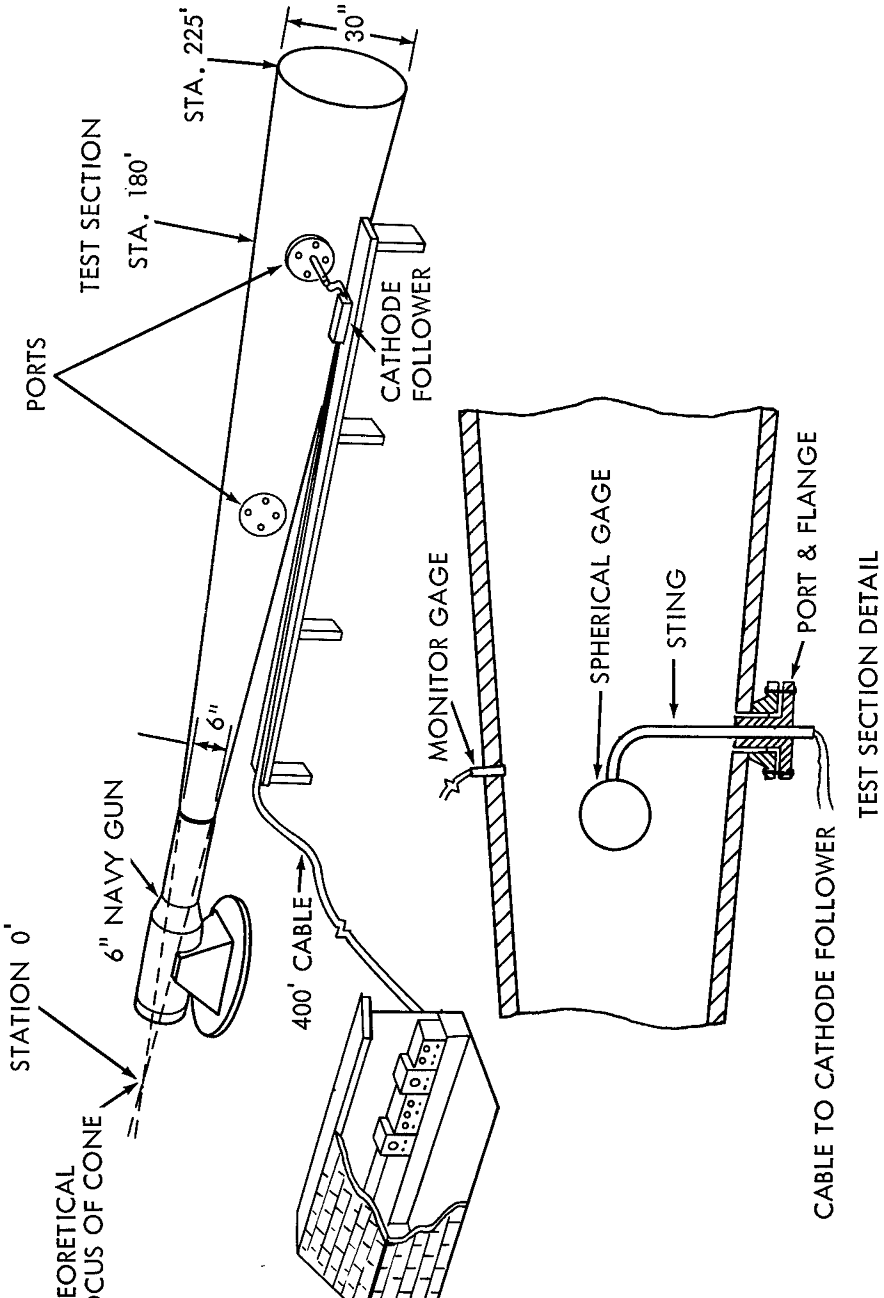


FIG. 16 EXPERIMENTAL SET-UP FOR PRELIMINARY RESPONSE EVALUATION

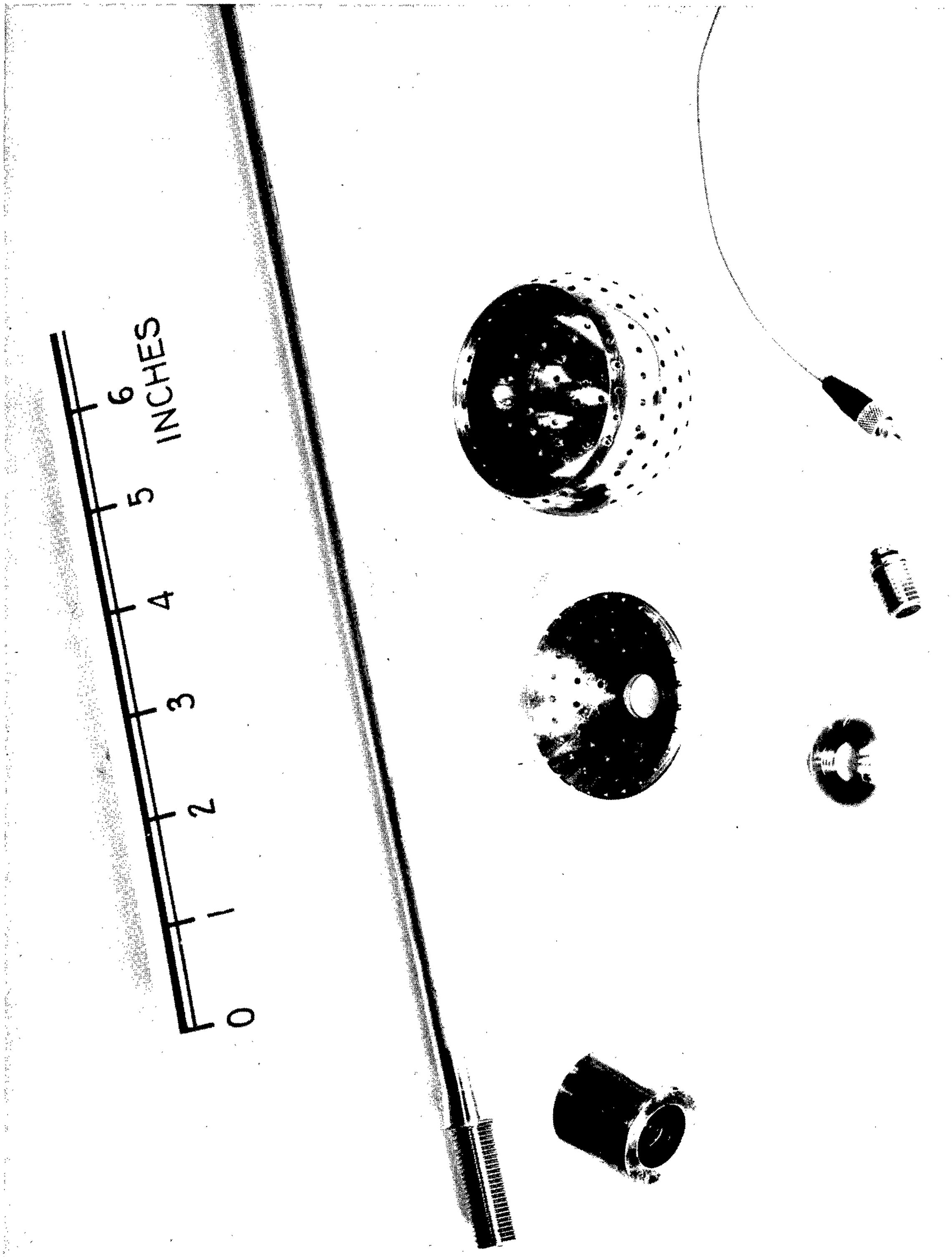


FIG. 17 STRAIGHT STING, SIMULATED CCC MOUNT, VENTILATED SPHERE CLAMP RING AND LC-70 PIEZO ELECTRIC TRANSDUCER

PRELIMINARY RESULTS, RESPONSE TIME

The response times indicated on all preliminary results in the NOL conical shocktube indicate that the predictions of the preliminary analysis were successful in estimating the response characteristics of the ventilated sphere.

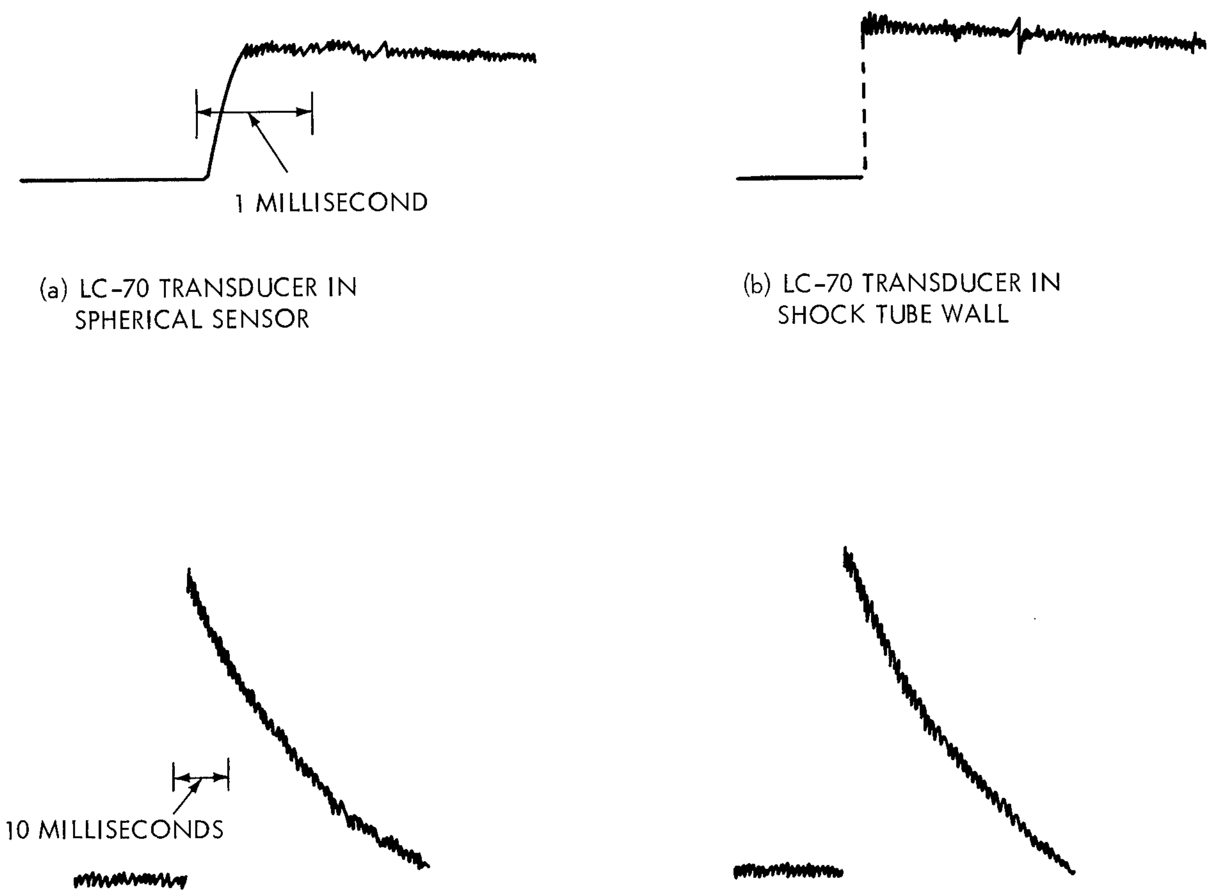
The analysis indicated that conditions approaching equilibrium should be present within 4/5 to 5/10 millisecond and test results indicated response times of approximately 3/10 to 4/10 millisecond. Since the pulse in the shocktube starts to decay immediately after reaching peak pressure while the analytical solutions should asymptotically approach some equilibrium value of pressure, exact comparison of response times is difficult. In general, however, the results indicate that the response of the present sensor configuration is close to optimum for this application.

The flat diaphragm gage was used as well as the LC-70 gage in initial evaluation of the sensor. The ringing or resonance that has been exhibited with some previous sensors was not experienced with the present sensor. This indicates that sizing and ventilation are approximately correct for this application and the cavity is acting as a plenum chamber.

The general results indicated are qualitatively represented in figure 18. The drawings represent data from actual oscillograph records of preliminary tests at 6 psi overpressure. The upper two traces compare the record of an LC-70 gage in the shocktube wall with an LC-70 located inside the sensor. The response time and general pulse shape indicate that the sensor is performing approximately as predicted.

The lower traces compare the CCC transducer (variable reluctance gage) in the sensor with an LC-70 piezoelectric gage in the wall of the shocktube. The lack of "ringing" or diaphragm resonance is indicated by the smooth trace. Again general response and pulse shape appear satisfactory. The return to zero overpressure for the sensor appears to be slightly late in preliminary test results. Since "ringing" appears to be no problem with the present configuration, the pulse slope might be improved by increasing the ventilation slightly. Such trade offs should be investigated in future designs.

Preliminary tests in the conical shocktube have demonstrated the feasibility of the basic concept and of the design procedures and sizing analysis. Quantitative evaluation of omnidirectional



(a) LC-70 TRANSDUCER IN SPHERICAL SENSOR

(b) LC-70 TRANSDUCER IN SHOCK TUBE WALL

(c) CCC TRANSDUCER IN SPHERICAL SENSOR

(d) LC-70 TRANSDUCER IN SHOCK TUBE WALL

FIG. 18 PRELIMINARY DATA TRACES SHOWING RESPONSE AND RESONANCE CHARACTERISTICS OF THE OMNIDIRECTIONAL GAGE (~6 PSI OVERPRESSURE) (VERTICAL DEFLECTIONS SCALED TO ELIMINATE CALIBRATION CONSTANTS)

characteristics and gage accuracy will require more thorough investigation in other facilities. Some semi-quantitative results and general conclusions can be summarized from the preliminary tests, however.

The results shown in figure 19 are typical of the conical shocktube evaluation at zero degrees angle of attack. Test results have been plotted on the theoretical curves of figure 8. Readings of the monitoring gage have been plotted as "actual overpressures" and readings from the spherical sensor have been plotted as "measured overpressures." As can be seen from this figure, only a small error would be encountered if the theoretical curve were used for the uncalibrated gage.

Bar symbols are shown to indicate the estimated mean scatter in the data from the preliminary tests in the conical shocktube. The quantity of data is not sufficient to permit a statistical evaluation. Several factors contribute to the scatter shown here, such as method of reading the record traces, difficulty in repeating shot conditions and lack of an exact standard for comparison of peak pressure rise (only one monitor gage was used in each case).

The tests were not run for angles of attack between 0 degrees and 45 degrees, but experience has shown that when the sting or mount is located in the wake region of the sphere (140 degrees to 220 degrees) the effect of the sting on the pressure distribution between 90 degrees and 270 degrees is small. It appears justified to assume, therefore, that the results indicated in figure 19 should be relatively insensitive to flow direction or direction of oncoming shock wave between approximately ±30 degrees. Wind tunnel results also support this assumption. This degree of omnidirectionality with such a small error for an uncalibrated gage represents a significant improvement over other gages.

At angles of attack from 45 degrees to 120 degrees the error for the uncalibrated gage becomes much more severe as indicated in figure 20. This is probably due to the effect of the sting and results because the theoretical curve based on an assumed value of $\overline{C}p$ is now quite unrealistic. The data can be considered to group (considering the scatter inherent in these measurements) about a mean line such as the one faired in the figure.

Using such a curve as the gage characteristic, a reasonable error would result for flow directions between 45 degrees and 120 degrees. The curve indicated is arbitrary and serves only to indicate a typical experimental mean. Experimental scatter

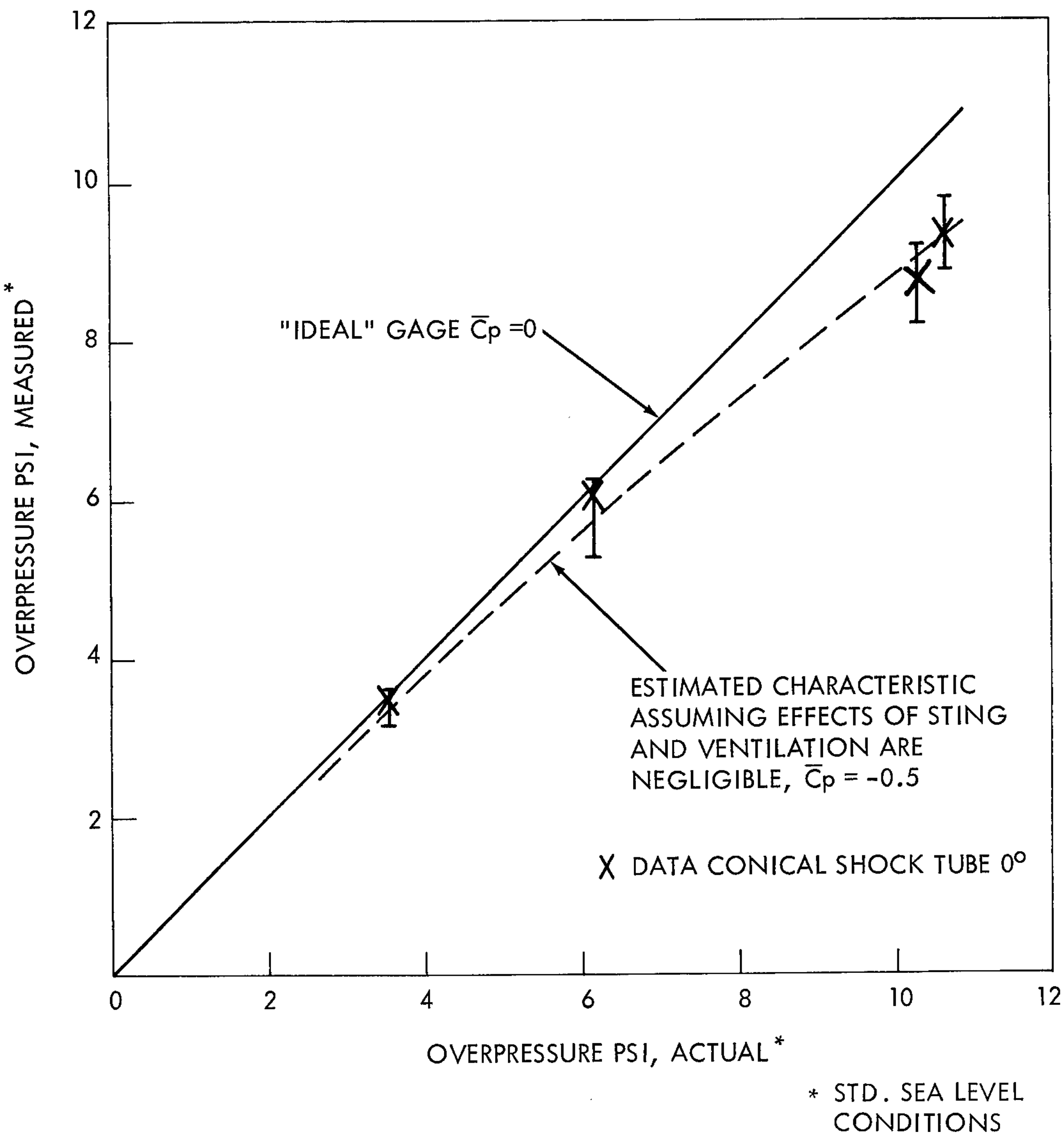


FIG.19 PRELIMINARY RESULTS AT 0°

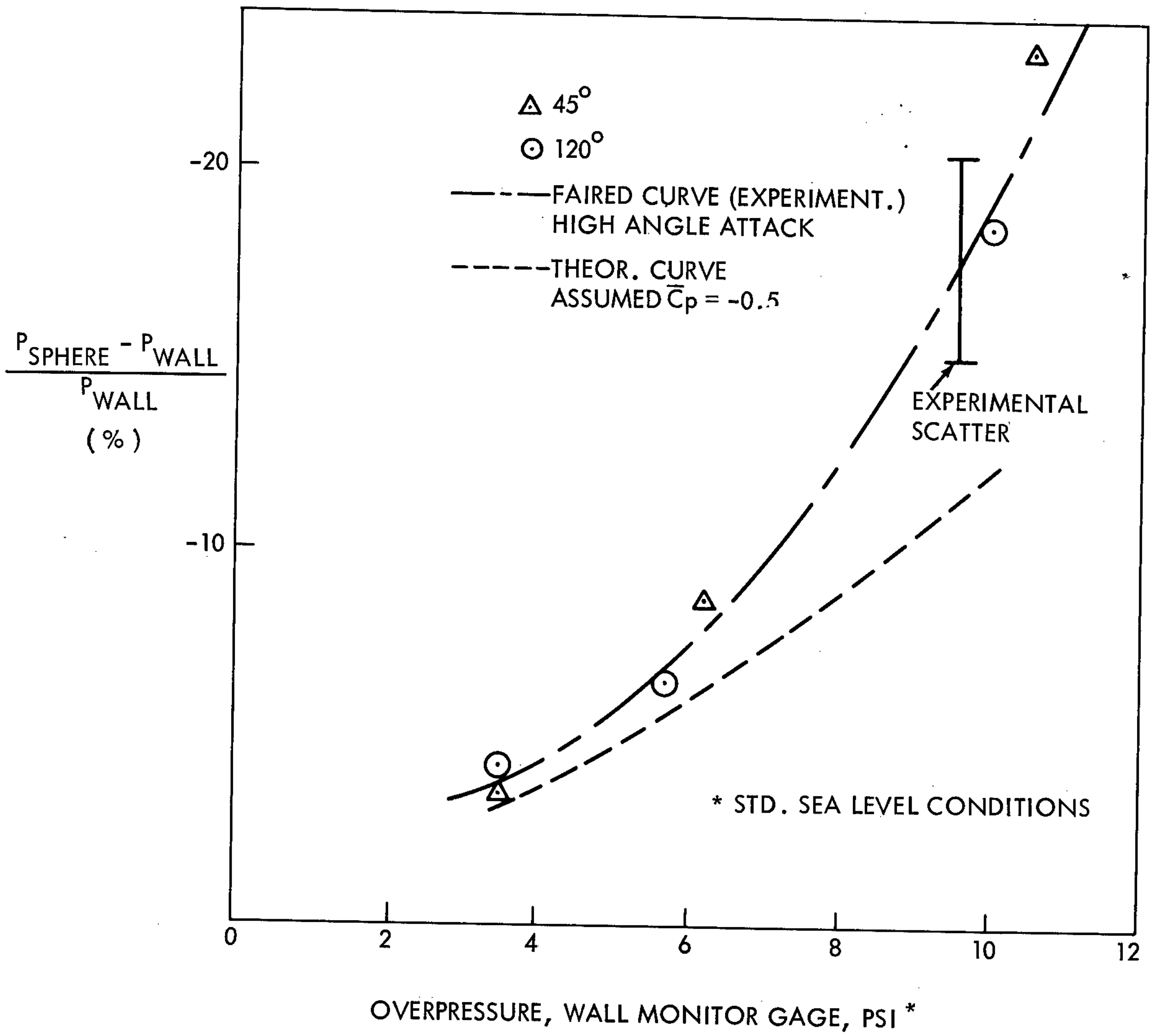


FIG.20 PRELIMINARY RESULTS AT HIGH ANGLES OF ATTACK

and other problems with the conical shocktube indicate that the gage is more accurate than indicated by these preliminary measurements.

CONCLUSIONS

Preliminary results indicate that the concept of a ventilated spherical sensor is feasible and warrants further refinement and calibration.

Properly applied, an uncalibrated sensor should exhibit good omnidirectional characteristics within a range of ±30 degrees.

With rough calibration and properly oriented, a single sensor should possess omnidirectional characteristics within a range of approximately ±70 degrees to an accuracy of approximately ±4 percent.

Using a combination of two gages, the omnidirectional range could be extended to approximately 180 degrees with small error and to greater values with moderate error. Limitations imposed by the preliminary test equipment indicate that gage capabilities are greater than preliminary results indicate. Simple modifications and calibration in selected facilities could possibly result in greatly improved accuracies and omnidirectional capabilities.

End

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APPENDIX A

The general case of a blast wave in air requires the treatment of a three-dimensional wave or shock front traveling outward from the source of explosion. A stationary pressure sensor overtaken or passed by the wave front will experience a discontinuous rise of pressure followed by a period of gradual decay. Figure A-1 represents the pressure time history that might be indicated by a pressure sensor acted upon by an explosion or blast wave.

In the case of the weak blast wave of interest in this application, the blast wave front will have traveled a large distance before encountering the gage. At the time of passage over the gage, the wave front will have expanded in size until the portion "seen" by the gage will exhibit initial characteristics similar to a plane wave front traveling across the gage followed by a slight pressure rise and a subsonic flow field.

These conditions are simulated in a shocktube of uniform cross section when the first shock front passes over a static pressure gage mounted in the tube or flush with its wall. Figures A-2 and A-3 indicate the sequence of events in a simple shocktube during the passage of time after a diaphragm is burst initiating moving shock fronts in the tube. Figure A-4 represents the static pressure time history recorded by a static pressure sensor located slightly to the right of the diaphragm location in the tube.

The pulse shape generated is dependent upon many factors such as length of tube, location of diaphragm, etc., and simulation of the exact pulse shape of Figure A-1 is not feasible.

The portion a-b of the pulse can be closely predicted and controlled, however, and response characteristics and qualitative calibration to a step pulse in pressure can be conveniently carried out in a one-dimensional shocktube. (Figure A-4)

RELATIONS FOR A SHOCKTUBE

Consider the conditions represented by figures A-2 and A-3 illustrating the conditions in a shocktube before and after a diaphragm is burst between two regions of different

pressure. Conditions of subscript 1 indicate ambient conditions surrounding the sensor before initiation of the shock front.

Applying the equations of Rankine-Hugoniot to a moving shock front, the following relations can be derived:

$$\frac{u_2 - u_1}{a_1} = \frac{\frac{2}{\gamma-1}\left[\frac{p_2}{p_1} - 1\right]}{\sqrt{\frac{2\gamma}{\gamma-1}\left[\frac{\gamma+1}{\gamma-1}\frac{p_2}{p_1} + 1\right]}}$$

The velocity change across a shock front can then be expressed as:

$$\Delta u = \frac{a_1 \; 5\left[\frac{p_2}{p_1} - 1\right]}{\sqrt{7\left[6\frac{p_2}{p_1} + 1\right]}}$$

If the conditions on the high pressure side of the diaphragm are denoted by subscript o and W_b represents the velocity of the plane shock wave after diaphragm burst (this simulates the blast wave) and W_c represents the velocity of the reflected shock from the closed end of the tube, we can write

$$\frac{p_1}{p_0} = \frac{p_1}{p_2}\left[1 - \frac{\frac{p_2}{p_1} - 1}{\sqrt{\frac{2\gamma}{\gamma-1}\left(\frac{\gamma+1}{\gamma-1}\frac{p_2}{p_1} + 1\right)}}\right]^{\frac{2\gamma}{\gamma-1}}$$

$$\frac{a_2}{a_1} = \sqrt{\frac{\frac{\gamma+1}{\gamma-1} + \frac{p_2}{p_1}}{\frac{\gamma+1}{\gamma-1} \quad \frac{p_1}{p_2}}}$$

$$M_2 = \frac{\frac{2}{\gamma-1}\left(\frac{p_2}{p_1} - 1\right)}{\sqrt{\frac{2\gamma}{\gamma-1} \quad \frac{p_2}{p_1}\left(\frac{p_2}{p_1} + 6\right)}}$$

$$\frac{W_b}{a_1} = \sqrt{\frac{\frac{\gamma+1}{\gamma-1} \quad \frac{p_2}{p_1} + 1}{\frac{2\gamma}{\gamma-1}}}$$

$$\frac{p_3}{p_2} = \frac{\left[\frac{\gamma+1}{\gamma-1} + 2\right] \frac{p_2}{p_1} - 1}{\frac{p_2}{p_1} + \frac{\gamma+1}{\gamma-1}}$$

$$\frac{a_3}{a_2} = \sqrt{\frac{\frac{\gamma+1}{\gamma-1} + \frac{p_3}{p_2}}{\frac{\gamma+1}{\gamma-1} + \frac{p_2}{p_3}}}$$

$$\frac{W_c}{a_1} = \frac{2\frac{p_2}{p_1} + \frac{2}{\gamma-1}}{\sqrt{\frac{2\gamma}{\gamma-1}\left(\frac{\gamma+1}{\gamma-1}\frac{p_2}{p_1} + 1\right)}}$$

$$\frac{W_c}{a_1} = \frac{\left(\frac{W_b}{a_1}\right)^2 + 2}{3\left(\frac{W_b}{a_1}\right)}$$

The parameters of interest for the range of overpressures required on this project are roughly plotted in figure A-5.

The portion of the pulse in figure A-4 indicated as a-b and a-b-c-d can be very useful for evaluating the dynamic response of a gage. This is most easily done in a good one-dimensional shocktube of adequate size.

A detailed study of the equilibrium pressures indicated inside a ventilated sphere for each condition of pressure, angle of attack and Mach number can best be made in a wind tunnel. This would correspond to portion b-c of figure A-4.

Portion c-d of the pulse could be studied using the expansion wave in a shocktube (equations a.1 - a.5), but other methods are more representative of the decay of blast wave pressure time pulses.

References (8) and (9) of the main report describe the use of conical shocktubes to simulate the pressure time characteristics of explosion waves.

The simple theoretical treatment used above for a one-dimensional shocktube is unfortunately not applicable to the conical tube, and control of operating conditions has not reached an equivalent state of the art. However, by using monitoring gages of known characteristics a facility such as that described in reference (9) can provide a rapid semi-quantitative evaluation of a blast wave sensor.

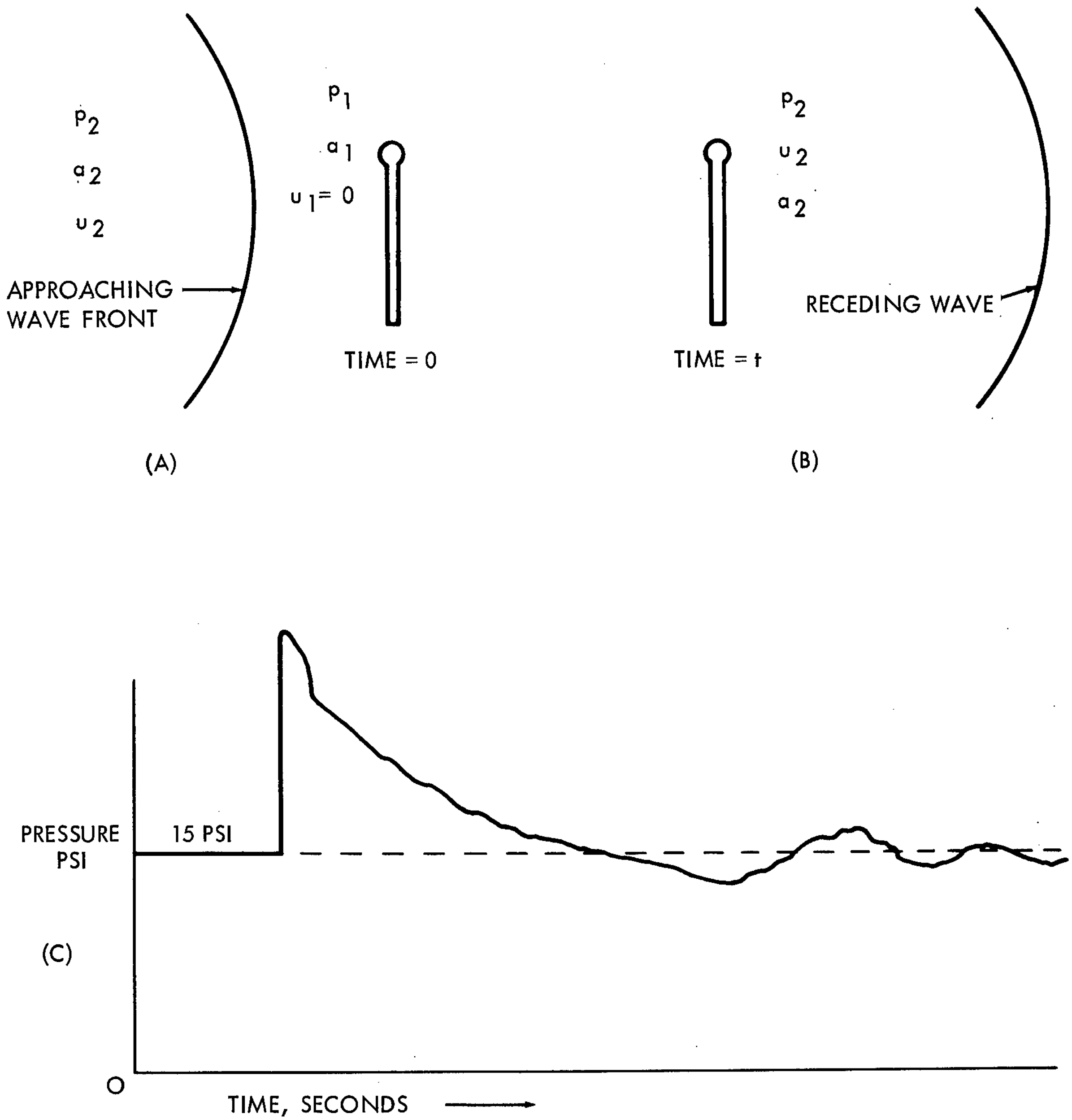
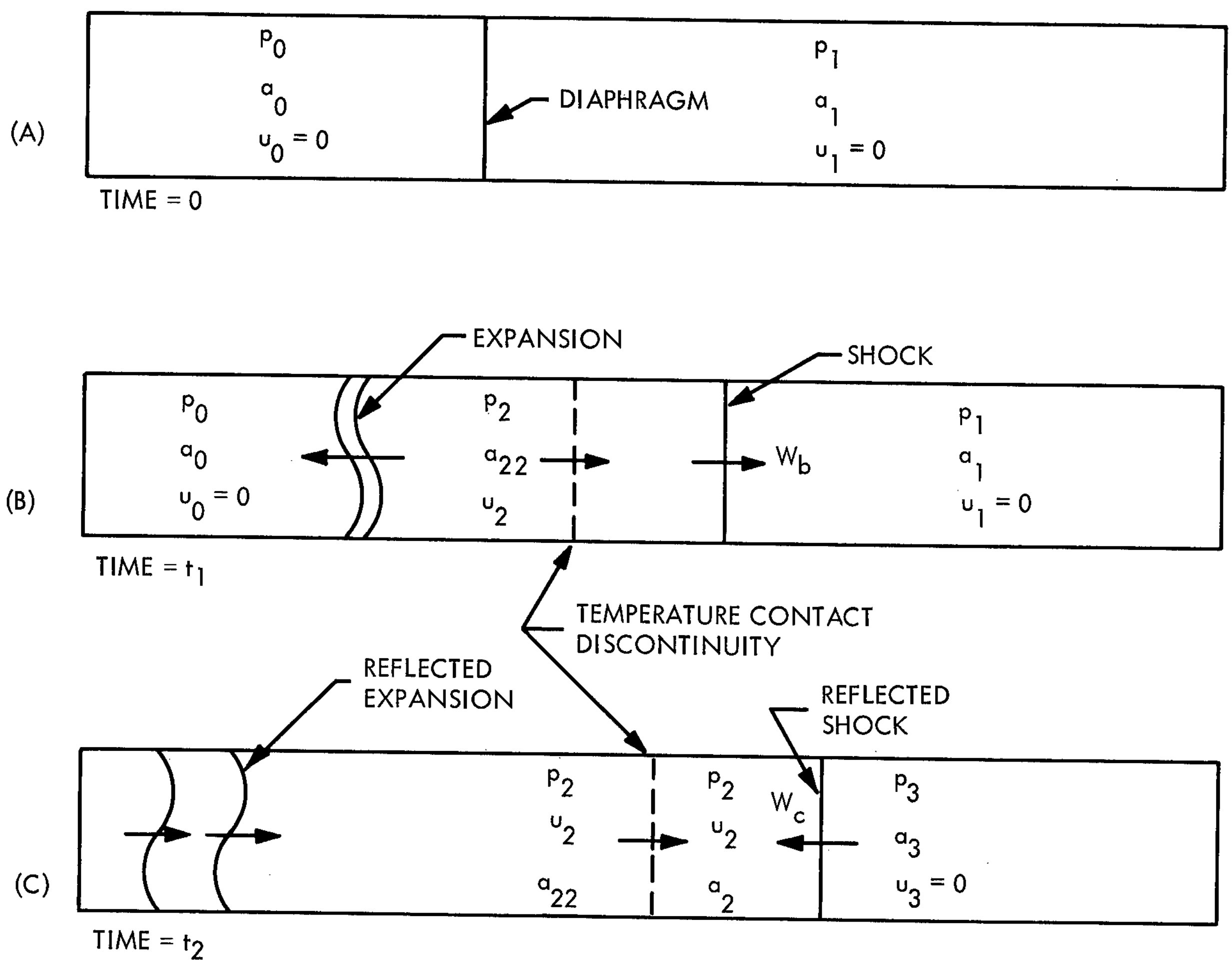


FIG. A.1 BLAST WAVE PASSING SENSOR



WHERE:
- p = PRESSURE, STATIC
- a = SPEED OF SOUND, LOCAL
- u = PARTICLE VELOCITY, LOCAL
- W = WAVE VELOCITY RELATIVE TO TUBE OR TO INITIAL AMBIENT CONDITIONS

SUBSCRIPTS

- 0 = CONDITIONS AT REST, HIGH PRESS. CHAMBER
- 1 = CONDITIONS AT REST, LOW PRESSURE CHAMBER, (EQUIVALENT TO AMBIENT CONDITIONS IN FRONT OF BLAST WAVE.)
- 2 = CONDITIONS BEHIND SHOCK
- 3 = CONDITIONS BEHIND REFLECTED SHOCK.

FIG. A.2 EVENTS IN SIMPLE SHOCK TUBE

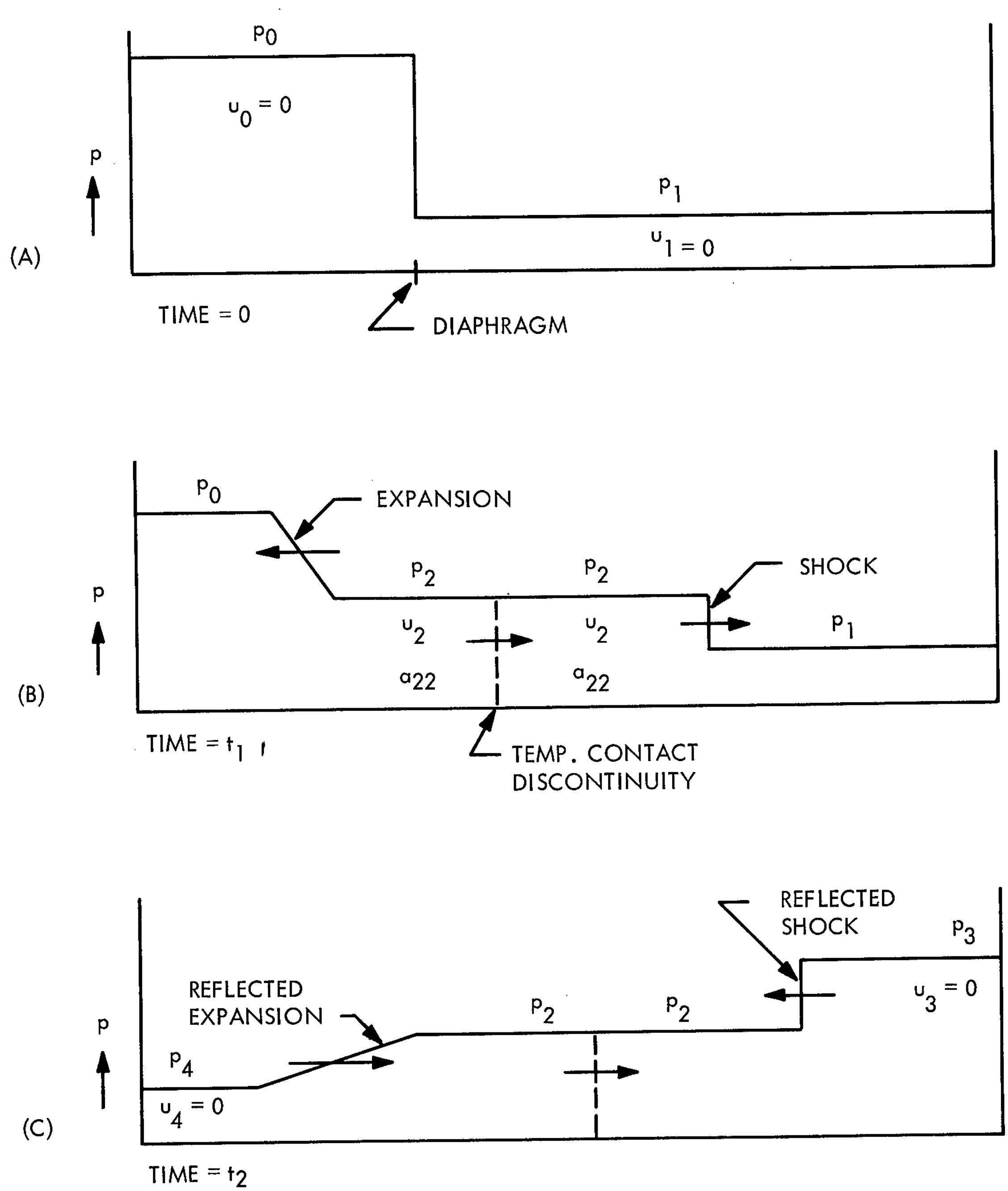


FIG. A.3 PRESSURE LEVELS IN SHOCK TUBE

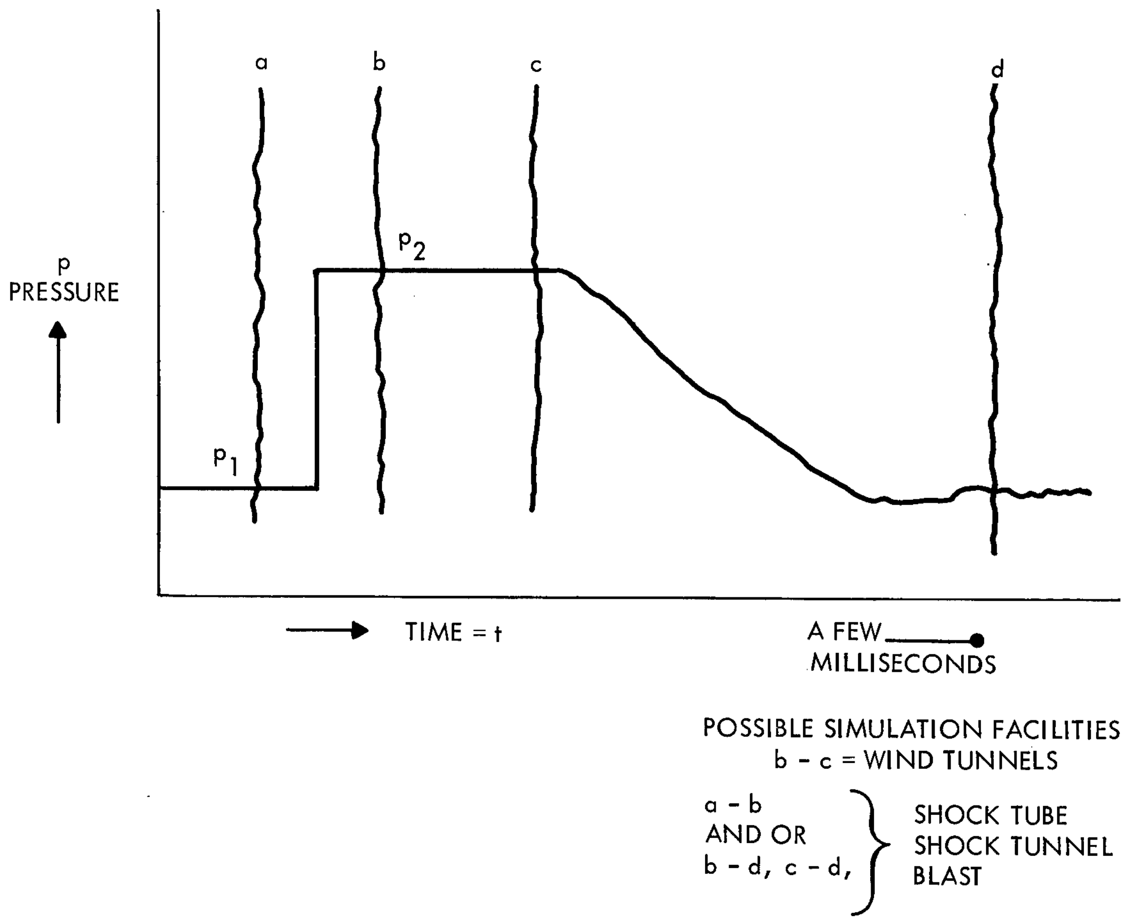


FIG. A.4 SIMULATION WITH PLANE WAVE

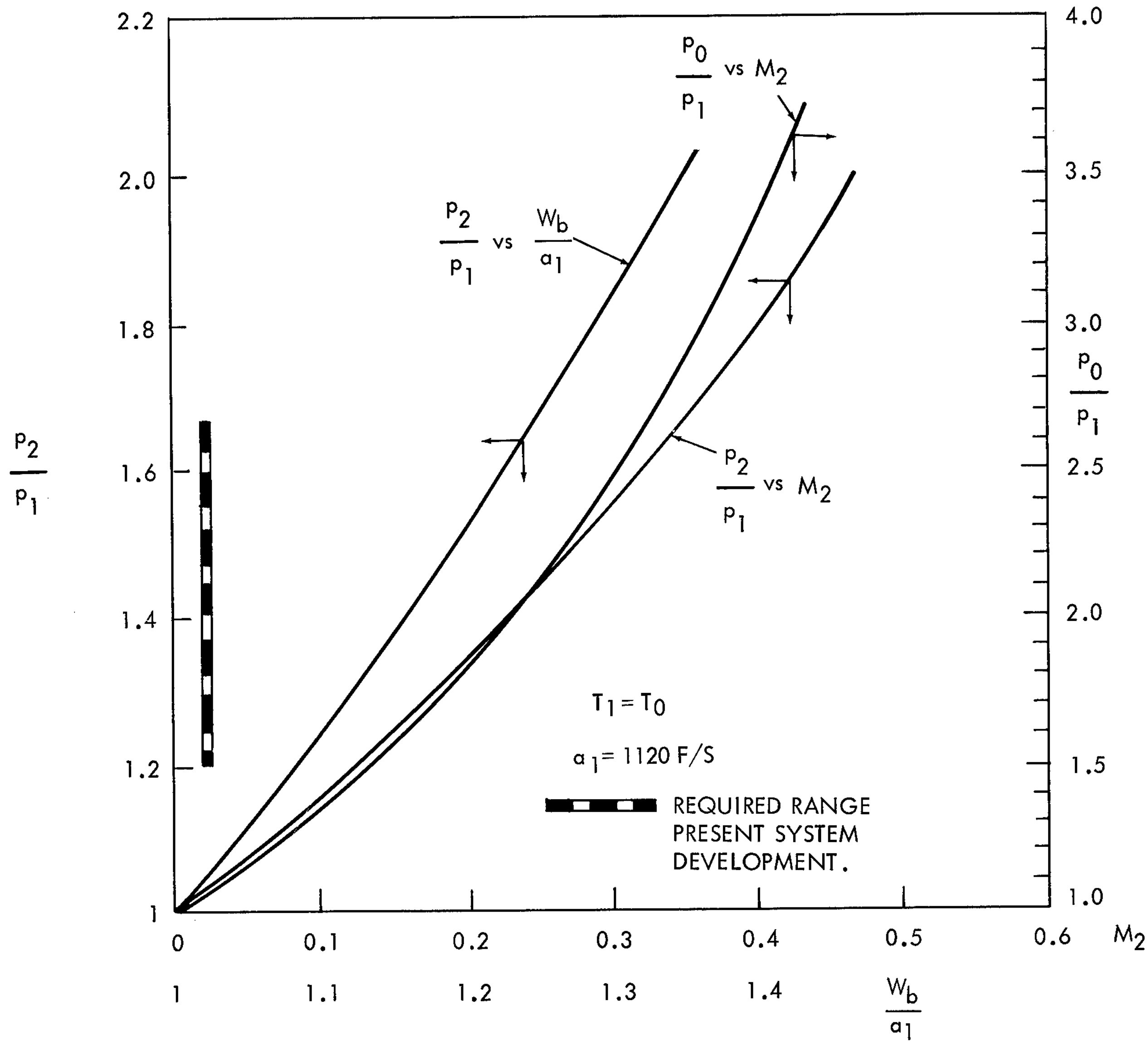


FIG. A.5 THEORETICAL UNSTEADY FLOW, ONE DIMENSIONAL

APPENDIX B

SIZING AND RESPONSE TIME ANALYSIS AND COMPUTATION

The actual mechanism by which a flow will be established and an equilibrium pressure reached inside the ventilated sphere is quite complex. A rigorous and accurate analytical treatment would probably require a large expenditure of time and effort and appears difficult or impossible without more knowledge of the actual conditions to be experienced in practice.

As a first approximation, however, a simplified analysis was made and a numerical program written to evaluate the characteristics of a configuration that would meet general requirements and establish an essentially constant internal pressure within approximately one millisecond. The following assumptions were made:

1. A representative pressure distribution can be assumed which is constant during the time period of interest.

2. This profile or distribution is established almost instantaneously at time = 0. (This assumption is in error only by the order of 1/10 of a millisecond, based upon preliminary analysis.)

3. The sphere walls are reasonably thin, and the ventilation holes are proportioned such that the flow into and out of the sphere approaches the type of flow to be expected through a thin plate orifice.

4. The internal cavity is large enough relative to individual ventilation openings so that the cavity acts essentially as a plenum chamber and secondary flows are not established.

Immediately after the passage of the shock, the exterior surface of the sensor is subjected to the pressures indicated by the pressure profile selected. The interior of the sphere, however, is essentially at the ambient pressure which existed before the arrival of the shock.

For the first increment of time, the flow through each orifice will be determined by the difference of the local pressure outside (as indicated by value on the pressure distribution curve at that location) and the pressure inside.

The rate of flow through each opening can then be expressed:

$$\text{Flow rate} = f\,(A,\ C_d,\ \Delta P,\ \delta)$$

Where: A = open area
C_d = flow coefficient
ΔP = pressure difference
δ = density

This flow can be an influx from outside into the sphere or an efflux from the interior outward depending upon the relative values of the pressures or the sign of ΔP.

By choosing small time increments and summating the individual flows over the entire sphere surface, a value for the net flow rate into the sphere during the time interval can be approximated.

Assumption of the compression process in the sphere (isothermal was used in this approximation) and use of the perfect gas laws will give a new value of internal pressure.

This numerical procedure is repeated until the pressure inside the sphere approaches an equilibrium or a value close to the average external static pressure. The time required for the pressure to reach the value indicated is considered the approximate response time for the combination of internal volume and ventilation used for the computation.

The program used for the preliminary configuration is outlined below. Modification to the equation for flow rate and new assumptions for the internal process will permit adaption of this program to other modes of ventilation.

NUMERICAL SPHERE VENTILATION SOLUTION

Summation Process

The summation process is a means of adding the effects of flow through seven chosen area increments (figure B-1) over each of which the local external pressure is considered a constant.

These regions of constant pressure are spaced equally from the forward portion of the sphere, i. e., every 30° beginning at $\theta = -15^\circ$. Each increment

of area is defined as: $A_i = 2\pi RH_i$ where H_i is the width of the ith area.

Each incremental area has the same percentage of ventilation, i.e., area through which the flow can pass. By knowing the ventilation, incremental area, free-stream density, discharge coefficient (orifice constant estimated at $C_d = .65$), and the pressure difference between the local external pressure and the internal sphere pressure, an equation for the incremental weight flow may be written and evaluated:

$$G_i = XA_iC_d \sqrt{2g\delta \Delta P_i}$$

where X = percent of area ventilated

A_i = incremental area (ft.^{2})

G_i = incremental flow rate (lb./sec.)

C_d = discharge coefficient

g = gravitational acceleration

δ = free-stream density

ΔP_i = P(local) - P(internal), (lb./ft.^{2})
If P_i is negative, the sign of G_i is negative.
If P_i is positive, the sign of G_i is positive.

By evaluating the G_i's and summing them over the seven increments, a net influx or efflux can be obtained. As the internal pressure approaches the free-stream pressure, the flow rate approaches zero and, therefore, equilibrium is approached.

The quantity that controls the flow rate is the internal pressure; therefore, a new internal pressure is determined for each time increment for which the summation process takes place.

For conditions inside the sphere let:

W_o = weight of gas in sphere before time incrementing (lb.)

W_i = weight of gas in sphere after time incrementing (lb.)

δ_o = density of gas before time incrementing (lb./ft.^{3})

δ_i = density of gas after time incrementing (lb./ft.^{3})

ΔW = change of gas weight between any two time increments (lb.)

G = net weight flow rate for any time increment

Δt = time increment (seconds)

V = cavity volume (ft.^{3})

$\Delta W = G \times \Delta t$

$W_o = \delta_o \times V$ (the first δ_o is given as S.S.L. air density)

$W_i = \delta_1 \times V$

$\delta_i = W_i/V$

from the equation of state for an isothermal process

$$P_i/\delta_i = P_o/\delta_o$$

$P_i = P_o \delta_i/\delta_o$ = the new value of the internal pressure to be used in the next summation process.

The process is continued until the sum of the time increments reaches an arbitrary preassigned value. This is done rather than letting the program run for the long period which may be necessary to let the net flow equal zero (attain equilibrium). Upon looking at the program results (such as in figures 9 and 10 of the main text), it can be determined whether equilibrium has been obtained or, if not, approximately how much more time would be required to reach an equilibrium condition. Due to an initial requirement of the system studied for this application, a limiting time of .7 millisecond was chosen.

The above approximation for the internal equilibrium pressure of a ventilated sphere was written as a FORTRAN program for the IBM 7090 digital computer.

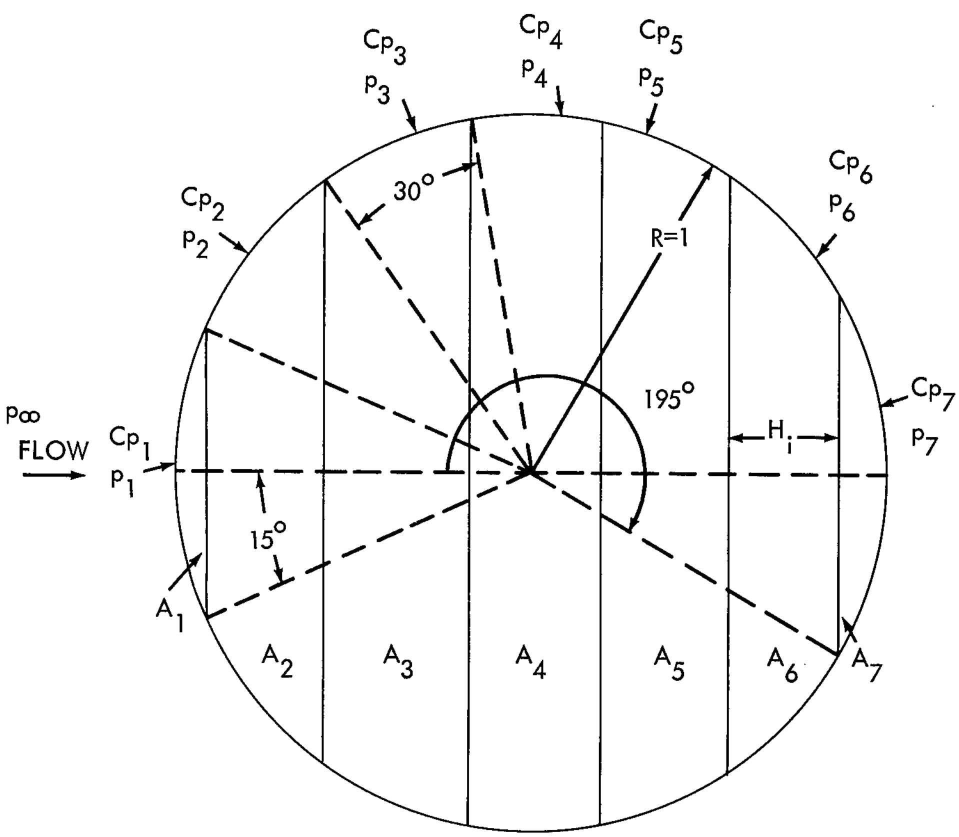


FIG. B.1 MODEL USED FOR RESPONSE COMPUTATIONS

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13. ABSTRACT

An aerodynamic sensor has been developed which is applicable to the measurement of the static pressure behind weak blast waves. The sensor is a ventilated sphere suitable for use with various types of electronic sensing units. A method used for prediction of response characteristics, ventilation coefficients, and sizing parameters gave good preliminary results in the range of 3 to 10 psi overpressures. Preliminary test results indicate a considerable increase in omnidirectional capability over previous gage types for this application. The preliminary program was limited to design of an experimental configuration and evaluation of concept feasibility.

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